The Journal of Child Psychology and Psychiatry

The Association for Child and Adolescent Mental Health

*Journal of Child Psychology and Psychiatry* **:* (2021), pp **–** doi:10.1111/jcpp.13463

# Is heart rate variability biofeedback useful in children and adolescents? A systematic review

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**Background:** Heart rate variability (HRV) is considered as an index of both physical and emotional health, and biofeedback aiming to increase the level of HRV has demonstrated extensive beneficial effects. Although HRV biofeedback is commonly and reliably applied in adults, the use of this technique, alone or in addition to other treatments, in children and adolescents has not been widely explored to date. **Methods:** This systematic review following PRISMA guidelines covers all human studies using HRV biofeedback in children and adolescents. A literature search was conducted in PsycINFO, PubMed and Scopus, and a standardized methodological quality assessment was performed. **Results:** Results showed the efficiency of HRV biofeedback sessions with children and adolescents to reduce physical and mental health-related symptoms and enhance well-being. **Conclusions:** These findings underline the therapeutic value of using HRV biofeedback as a complement to more conventional behavioural and cognitive interventions to help children to manage stress and/or pain. Capitalizing on the identified strengths and shortcomings of available results, we propose research avenues as well as evidence-based clinical guidelines for using HRV biofeedback in clinical paediatric settings. **Keywords:** Heart rate variability; biofeedback; cardiac coherence; stress; children.

## Introduction

While heart rate corresponds to the number of heartbeats per minute, heart rate variability (HRV) is a measure of the naturally occurring beat-to-beat changes in heart rate (McCraty & Shaffer, 2015). A healthy heart is not a metronome as its oscillations are complex and constantly changing, thus allowing the cardiovascular system to adjust rapidly to sudden physical and psychological challenges to homeostasis. HRV is therefore an excellent indicator for assessing the activity of the autonomic nervous system, both at the peripheral and central levels, as well as the balance between the two branches of the sympathetic and parasympathetic nervous systems (Thayer, Åhs, Fredrikson, Sollers, & Wager, 2012).

Various metrics are used to quantify HRV through electrocardiographic (ECG) signals or photoplethysmography (PPG). Time-domain indices of HRV quantify the amount of variability in measurements of the interbeat interval (e.g. standard deviation of differences in interbeat intervals, root mean square of successive interbeat intervals), while frequency-domain measurements estimate the distribution of absolute or relative power into frequency bands (e.g. high-frequency power). A high amplitude of HRV is associated with better emotion regulation and the use of adapted coping strategies or resilience (Fabes & Eisenberg, 1997). Importantly, a significant decrease in HRV amplitude is identified as a sign of vulnerability to stress and has been reported in various populations of patients with psychiatric or behavioural disorders, such as severe depression, post-traumatic stress disorder or generalized anxiety (Lehrer, 2007; Servant, Logier, Mouster, & Goudemand, 2009; Wheat & Larkin, 2010).

HRV biofeedback is considered a simple and non-invasive technique to act upon autonomic activity, mainly through the regulation of breathing in response to external feedback, to enhance heart–brain synchronization and facilitate the maintenance of a physiologically efficient inner state (Prinsloo, Derman, Lambert, & Rauch, 2013). Overall, biofeedback is a training technique that teaches individuals to recognize and learn how to modify their body's physiological signals to help improve health and performance (Schwartz & Andrasik, 2017). Various physiological parameters (e.g. heart rate, electrodermal activity, brain activity) can be measured and visualized in real time. The immediate feedback helps individuals to gain voluntary control over the various physiological processes and to bring about favourable changes (Yu, Funk, Hu, Wang, & Feijs, 2018). The main aim of HRV biofeedback is to increase cardiac vagal tone. The subject receives feedback regarding their current HRV and, depending on the intervention protocol used, they learn how to handle various techniques (e.g. slow breathing or resonant frequency diaphragmatic breathing) to achieve their optimal individual HRV level (Prinsloo, Rauch, & Derman, 2014). HRV biofeedback can be provided by handheld devices (e.g. emWave2 or Stress Eraser), computer-based interactive programmes (emWave desktop or Journey to Wild Divine) or with professional ECG recording equipment. The number of HRV biofeedback applications for smartphones is also increasing (Prinsloo et al.,

Conflict of interest statement: No conflicts declared.

2014). Most individuals effortlessly achieve high-amplitude oscillations in HRV after a few minutes of training, and almost everyone can master the technique within one to four sessions of coaching. HRV is thus easily and rapidly learned and can be implemented at little cost.

The effectiveness of HRV was confirmed by recent meta-analyses (Goessl, Curtiss, & Hofmann, 2017; Lehrer et al., 2020), demonstrating that HRV biofeedback is associated with a variety of health benefits in both healthy and pathological adult populations. Levels of anxiety and depressive stress-related symptoms were significantly reduced (e.g. Caldwell & Steffen, 2018; Tan, Dao, Farmer, Sutherland, & Gevirtz, 2011), and various kinds of human performance including cognitive, physical and creative activities were improved (e.g. Paul & Garg, 2012; Sutarto, Wahab, & Zin, 2013; Wells, Outhred, Heathers, Quintana, & Kemp, 2012). Alone or combined with other relaxation or breathing techniques, HRV biofeedback has proved very useful and has become increasingly used by psychotherapists in several adult pathological populations (Lehrer, 2018; Leyro, Buckman, & Bates, 2019). However, its use and health benefits in children and adolescents have received little attention to date. This is all more surprising given that children are ideal potential users (e.g. Attanasio et al.,1985; Culbert, Kajander, & Reaney, 1996): (a) having a naturally higher HRV level, they are very sensitive to guided paced breathing; (b) in general, they can easily control their physiological parameters (e.g. peripheral temperature, breathing and heart rate) via biofeedback techniques; (c) thanks to their enhanced brain plasticity, they can easily learn new emotional self-regulation techniques; and (d) they are also very familiar with and curious about new technologies as well as the use of biofeedback video games systems.

The main objective of the present study was to propose the first systematic review specifically focussing on the use of HRV biofeedback in children and adolescents. Following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, it reports the effectiveness of HRV biofeedback, alone or combined with other methods such as psychoeducation or relaxation, to reduce physical and mental health-related symptoms and enhance well-being, by comparing the results from published studies investigating HRV biofeedback in children and adolescents with or without physiological and/or mental disorders. The methodological quality of the intervention studies including a direct comparison with a control group was also evaluated by a quality assessment tool developed by the National Heart, Lung and Blood Institute (NHLBI, 2014). Based on the collected data and the observed results and conclusions, the second objective was to propose directions for future research and clinical applications of HRV in children and adolescents.

## Methods

### *Identification of articles and selection procedure*

This systematic review was carried out following the PRISMA guidelines, which include a checklist of 27 items and a flow diagram (Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2009). To identify eligible studies, a literature search was performed in PubMed, Scopus and PsycINFO. We focussed on peer-reviewed articles published in English between 1 January 1999 and 1 January 2020, while grey literature (unpublished convention papers, dissertations, etc.) was not included. The search strategy used the following syntax: ("heart rate variability biofeedback" OR "HRV biofeedback" OR "heart rate coherence biofeedback" OR "heart rate coherence" OR "cardiac coherence" OR "respiratory sinus arrhythmia biofeedback") AND ("child*" OR "adolescen*"). The initial search identified 139 articles (47 in PubMed, 44 in Scopus, 48 in PsycINFO). The reference list of these articles was screened, and 6 additional papers were identified. The articles to be included in the review

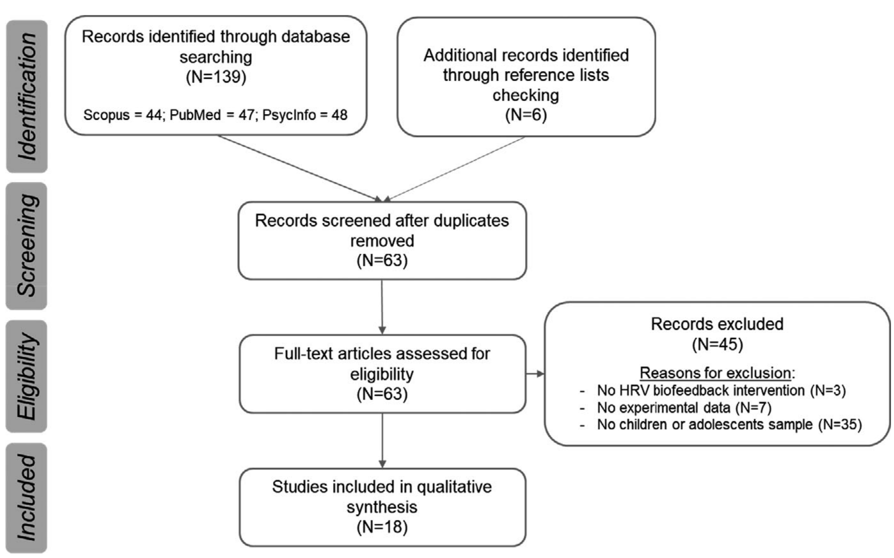


**Figure 1** PRISMA flow diagram describing process for selecting and reviewing papers included

were then selected according to the PRISMA procedure (Figure 1): First, duplicates were removed, leading to the identification of 63 unique papers. Second, remaining records were individually screened and articles presenting one of the following exclusion criteria were removed: (a) no HRV biofeedback intervention; (b) no peer-reviewed experimental data or case reports presented (i.e. review, reply, editorial, erratum, conference proceedings, dissertation); and (c) no sample of children or adolescents. It is worth noting that articles with a mixed sample of adolescents and young adults (under 22 years old) were included in our selection strategy. This procedure ended up in the inclusion of 18 articles in the systematic review process.

### Methodological quality assessment

The methodological quality of each study including control group comparisons ($n = 10$) was assessed using the 'quality assessment of controlled intervention studies' scale developed by the NHLBI (2014). The scale comprises 14 items (Appendix S1) with a binary answer (Yes/No), leading to a maximum score of 14. For each study, a score (i.e. percentage of items with a 'Yes' answer) was computed, leading to a global quality rating (i.e. poor for scores below 50%, fair for scores between 50 and 69%, good for scores between 70% and 79%, and strong for scores of 80% and beyond, adapted from Black et al., 2017). When an item was not directly relevant to the study or when the information contained in the paper did not allow a clear decision regarding an item to be made, the term 'not applicable' (NA) or 'not reported' (NR), respectively, was used and the item was excluded from the computation of the global quality rating. Table S1 reports detailed scores obtained for each study on each item and global quality ratings.

### Data extraction and synthesis

Regarding the 18 studies using HRV biofeedback intervention in children and adolescents, a systematic data extraction procedure was used to determine the main characteristics of each article. Four categories of variables were reported, adapted from the PICOS procedure (Liberati et al., 2009): (a) participants (population, sample size, mean age, age range and gender ratio); (b) intervention (HRV biofeedback, other interventions, number of sessions, duration of a session, HRV measures, assessment tools, time measurement and follow-up); (c) comparison (control group, matching variables); and (d) outcomes (main results, effect sizes, reported limitations and key conclusion). A comprehensive synthesis of the data extracted from each study is presented in Table 1.

## Results

### Quality assessment

Among the 10 studies with a control group comparison included, only 1 was considered as presenting strong quality, 1 good quality and 8 fair quality, according to the assessment criteria selected (Table S1). Most of the studies reported good adherence to the intervention protocols in both experimental and control groups, and the overall dropout rate was quite low across studies and did not differ greatly between treatment groups. Before conducting the intervention trial, most studies generated hypotheses, reported the outcomes to be measured and prespecified the groups to be analysed. The implementation and assessment of clinical and physiological outcomes were good, all studies using valid and reliable methods, tasks or questionnaires to do so, and all participants were analysed according to the group they were assigned to (e.g. intervention or control group). However, half of the studies (i.e. 5 out of 10) reported an adequate randomization method and only one study was blind regarding the outcomes' analysis (i.e. people assessing the outcomes were not aware of the condition assigned to the participants). Most studies attempted to match the experimental and control groups on the main sociodemographic variables (e.g. age, gender), but several studies did not manage to constitute equivalent groups. Finally, most studies did not justify their sample size based on a priori power computation or previous experiments.

### Main outcomes

Each of the included studies focussed on the benefits derived from HRV biofeedback intervention in children and adolescents without any disturbance or disorder ($n = 3$), or presenting either physiological ($n = 6$) or mental health disorders ($n = 9$). Among these studies, 7 included in their sample only children (i.e. <15 years old), 3 only adolescents (i.e. >15 years old), while the other 8 studies considered both children and adolescents[1]. These studies are described below, and their main characteristics are synthesized in Table 1.

*HRV biofeedback in healthy children and adolescents.* Two studies evaluated the beneficial influence of a classroom-based emotional self-regulation programme, which included several sessions of HRV biofeedback in a school setting (Bradley et al., 2010; McCraty, Atkinson, Tomasino, Goelitz, & Mayrovitz, 1999). Middle-school children (12 and 13 years old) were enrolled in an emotional competence intervention (16 hr given over 2 weeks) during which they had to learn a series of tools and strategies to help them to reduce stress, to improve communication skills, to maintain focus on academic contents and to enhance relationships with others (McCraty et al., 1999). In the first group ($n = 32$), psychological and behavioural changes were examined one week before and one week after the training programme. The results of this study showed several significant improvements among trained students such as better management of stress and anger, higher levels of motivation and concentration, and enhanced leadership and communication skills. Interestingly, most of these changes were still observed 6 months later. In a second phase, the impact of the training on children's autonomic responses was assessed before, during and after a stressful interview. Half of the participants followed the intervention course (i.e. experimental group; $n = 30$), while the other half did not (i.e. passive control group; $n = 30$).

**Table 1** Description and main results of HRV biofeedback intervention studies with healthy and pathological child and adolescent populations

| | Participants | | | | | Intervention | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Authors (year) | Population | Sample (N) | Mean Age (± SD) | Age Range | Gender ratio (% males) | HRV Biofeedback Intervention | Coupled with (other interventions) | Number of sessions | Duration of each session | HRV measures |
| **Healthy Populations** | | | | | | | | | | |
| Children only (<15 years old) | | | | | | | | | | |
| McCraty et al., (1999) | Middle-school students | Year 1: $n$ = 32; Year 2: Experimental group $n$ = 30, Control group $n$ = 30 | Year 1: $M$ = 12.2; Year 2: $M$ = 13.2 | Year 1: 12–13; Year 2: 12–14 | Year 1: 56.25; Year 2: Experimental group = 36.67, Control group = 30 | Freeze-framer interactive learning system | Heart Smart program | NR | NR | RR intervals; SD of RR intervals; High and Low frequency power; Total power; Coherence ratio |
| Adolescents only (>15 years old) | | | | | | | | | | |
| Dziembowska et al., (2016) | Young male athletes | Biofeedback group: $n$ = 20; Control group: $n$ = 21 | $M$ = 18.34 ± 1.36 | 16–21 | 100 | emWave PC stress relief system | No | 10 in 3 weeks | 20 min | HRV and EEG recordings; Coherence Index |
| Both Children and Adolescents | | | | | | | | | | |
| Bradley et al., (2010) | High-school students | Experimental group: $n$ = 77; Control group: $n$ = 59 | Experimental group: $M$ = 15.3 ± 0.44; Control group: $M$ = 15.3 ± 0.44 | NR | Experimental group: 53; Control group: 40 | Freeze-framer interactive learning system | TestEdge program | NR | NR | RR intervals; SD of RR intervals; High and Low frequency power, Total power; Coherence ratio |
| **Populations with physical and/or mental health disorders** | | | | | | | | | | |
| Children only (<15 years old) | | | | | | | | | | |
| Amon and Campbell (2008) | Children with ADHD | Experimental group: $n$ = 24 (17 in group 1; 7 in group 2); Control group: $n$ = 12 (10 in group 1; 2 in group 2) | Experimental group: $M$ = 9.5; Control group: $M$ = 8.75 | 5–14 | Experimental group: 62.5; Control group: 75 | The Wild Divine biofeedback video game | / | Group 1: 12 sessions (once a week); Group 2: 24 or 36 sessions (twice or three times a week) | 45 min | / |
| Kenien (2015) | Children with emotional disturbances | Treatment group: $n$ = 30; Control group: $n$ = 33 | NR | 7–14 | 87 | emWave desktop HRV biofeedback | / | 20 sessions over 12 weeks | 20 min | / |
| Lloyd et al., (2010) | Children with ADHD | Total $n$ = 38 (only biofeedback group: $n$ = 14; both biofeedback and placebo: $n$ = 22; only placebo group: $n$ = 2) | NR | 9–13 | 89.7 | emWave Desktop System | / | One daily session over 6 weeks | 20 min | / |
| Pop-Jordanova (2009) | Children with mental health disorders (6 groups: (1) Children with anxious phobic symptoms; (2) children with somatoform problems; (3) children with obsessive-compulsive manifestations; (4) children with ADHD; (5) children with conduct disorders; (6) control | (1) $n$ = 15; (2) $n$ = 15; (3) $n$ = 7; (4) $n$ = 10; (5) $n$ = 12; (6) $n$ = 15 | (1) $M$ = 12.5 ± 2.25; (2) $M$ = 10.92 ± 2.06; (3) $M$ = 14.5 ± 2.2; (4) $M$ = 10.5 ± 1.8; (5) $M$ = 11.5 ± 1.52; (6) $M$ = 10.18 ± 1.33 | NR | NR | Heart Math Freeze-Framer system (basic recordings + 2 games) | / | 15 training sessions | 16 min | HRV spectra: % of low, medium and high HRV |
| Shockey et al., (2013) | Children diagnosed with cancer | $n$ = 12 | $M$ = 11 ± 2.08 | 8–14 | 58.3 | Heart Math emWave | Relaxation (belly breathing) | 3 | 30 min | HR and HRV Coherence score |
| Slutsker et al., (2010) | One boy with cyclic vomiting syndrome (CVS) | $n$ = 1 | 13 | NA | 100 | emWave program | Cognitive behavioural therapy (CBT) | 16 sessions over 4 months | NR | Low/high frequency ratio |
| Adolescents only (>15 years old) | | | | | | | | | | |
| | Adolescents with chronic pain | $n$ = 4 | $M$ = 16 ± 1 | 15–17 | 25 | | | 3 or 4 | NR | |

| | | | Comparison | Outcomes | | | |
|---|---|---|---|---|---|---|---|
| Assessment tools | Time measurement | Follow-up | Control group | Main results | Effect Sizes | Limitations reported | Key conclusions |
| The Achievement Inventory Measurement (AIM) | Year 1: One week before and one week after the completion of the programme + follow-up; Year 2: HRV recordings before, during and after a stressful interview | After 6 months postintervention | Yes (no intervention) | AIM assessment: Significant improvement in 11 of 19 subscales following intervention. Many of these changes were sustained over the following 6 months. Physiological assessment: Significant increase in heart rate, standard deviation of RR intervals, total power and VLF power in trained group. | NR | Small sample size; no appropriate controls; no simultaneous measurement of behavioural and physiological changes | Results provide support for integration in school curricula of courses designed to teach effective self-management skills to children. |
| State-Trait Anxiety Inventory (STAI); Rosenberg self-esteem Scale (SES) | Preintervention and postintervention | None | Yes (no intervention) | Biofeedback group showed changes in both EEG and HR measures. | NR | Small sample size; No generalization for both genders; Only short-term effects evaluated | HRV biofeedback is a simple and powerful tool for sport psychology. |
| Test Anxiety Inventory; Test performance; Stroop Test | Twice: preintervention and postintervention; two phases of measures: Resting baseline and Stress preparation period | None | Yes (no intervention) | Experimental group showed lower test anxiety and increased psychophysiological coherence after intervention. Students with high test anxiety exhibited increased HRV and heart rhythm coherence even during resting baseline condition. | $d$ = Between 0.31 and 0.89 | Lack of baseline equivalence between the two groups; No information about native language; Stroop Test was not an achievement test | Students in intervention group appeared to have effectively learned, practiced and integrated the emotion self-regulation skills taught in programme. |
| ADHD questionnaires; Strengths and Difficulties Questionnaire (SDQ); Questionnaire on the Wild Divine Video game | Parents completed an online questionnaire 4 times: T1 Preintervention, T2 after the 1st month, T3 after the 2nd month, T4 after the 3rd month | None | Yes (no ADHD) | Both experimental and control group had significant reductions on SDQ and ADHD questionnaire, resulting in improvement in behaviour by final session. | Only for Wilcoxon Test $r$ = 0.54 | Small and uneven sample size; no random group allocation | The Wild Divine protocol showed potential in teaching breathing and relaxation techniques to reduce disruptive behaviours in children with ADHD. |
| Behaviour Rating Inventory of Executive Function (BRIEF): 4 Subscales = Inhibition, Working Memory, Emotional Control and Shift | Completed by teachers 1 week prior to and 1 week postintervention | None | Yes (no intervention) | No significant difference between pretest and post-test within intervention or control group on all subscales. | NR | Secondary data analysis of a quasi-experimental study design; No participant selection on specific inclusion and exclusion criteria; Wide age range; no randomization selection for control and treatment groups; minority of females | More objective measures and qualitative assessment are needed. |
| Cognitive Drug Research (Cognitive efficiency computer-based assessment); Strength and difficulties Questionnaire; Interviews with 32 parents | T1: preintervention; T2: postintervention (biofeedback or placebo); T3: postintervention (only for placebo groups) | None | Yes (active placebo) | Participants demonstrated significant improvements in various aspects of cognitive functioning such as delayed word recall, immediate word recall, word recognition, and episodic secondary memory. Significant improvements in behaviour were also found. | NR | Self-reported questionnaires | The intervention offers a physiologically based programme to improve cognitive functioning and behaviours in children with ADHD. |
| Eysenck Personality questionnaire and inventory | Preintervention and postintervention | None | Yes (but no direct comparison) | Maximum HRV changes obtained for obsessive-compulsive, conduct disorders, and anxiety. Children with ADHD did not manage to change high part of HRV. | NR | / | HRV as a peripheral biofeedback could be good choice especially for introvert children manifesting common mental health problems. |
| Faces Scale (anticipatory fear); State/Trait Anxiety Scale for Children (STAIC); Satisfaction with the intervention programme (Likert scale) | Preintervention and postintervention | None | None | Decrease in state and trait anxiety from baseline to final session; Improvement in coherence scores in sessions 3 and 4. | NR | Small sample size; No control group comparison; One-to-one interaction with the investigator; Faces scale modifications are not appropriate | This combination intervention of relaxation and biofeedback served as a tool to increase participants' awareness of the connection between emotions, physiological changes, and self-regulation. |
| Symptoms | Preintervention and postintervention + follow-up | After 4 months postintervention | None | Better HRV low/high ratio and symptom-free after intervention. Four months after therapy, no vomiting was reported. | NR | / | HRV biofeedback is possible to assist the patient regulate autonomic dysregulation. |
| / | | None | None | | NR | | |

(continued)

**Table 1** (continued)

| | Participants | | | | | Intervention | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Authors (year) | Population | Sample (N) | Mean Age (± SD) | Age Range | Gender ratio (% males) | HRV Biofeedback Intervention | Coupled with (other interventions) | Number of sessions | Duration of each session | HRV measures |
| Fahrenkamp and Benore (2019) | | | | | | Nexus 10 biofeedback system (BioTrace) | Interdisciplinary programme | | | Respiration rate; HRV (%LF) |
| Thurstone and Lajoie (2013) | Adolescent with cannabis use | $n = 1$ | 17 | NA | 100 | emWave Desktop Stress Relief | Cognitive behavioural therapy (CBT) | 6 | 10 min | HRV amplitude and power spectrum |
| Both Children and Adolescents | | | | | | | | | | |
| Goodman et al., (2018) | Children with diagnosis of Autism Spectrum Disorder (ASD) | $n = 15$ | $M = 12.4 \pm 2.5$ | 9–18 | 86.7 | Thought Technology Ltd. (Quebec, Canada) equipment and software (BioGraph Infiniti 6.0) | Group 1: HRV biofeedback alone - Group 2: HRV Biofeedback + Mu Rhythm Synchrony Neurofeedback (MRS-NFB) | Preliminary Training = 4 sessions + Training = 12 sessions | 1 hr | Quantitative EEG; Mu Suppression Index; Standard deviation of normal-to-normal wave intervals; Square root of the mean squared difference of successive normal-to-normal intervals; HF spectrum |
| Groeneveld et al., (2019) | Children with ADHD | $n = 100$ | $M = 10.6 \pm 2.9$ | 6–17 | 72 | Finger Blood Volume Pulse (BVP) sensor and respiration belt; Fluctuation of HR interbeat intervals presented on a monitor | Neurofeedback (NFB) breathing exercise; Psycho-education | 30 | 3 to 5 min | HRV; Breathing Rate and QEEG |
| Knox et al., (2011) | Children with anxiety | Total $n = 24$ (Intervention group: $n = 12$; Control group: $n = 12$) | $M = 12.88 \pm 2.42$ | 9–17 | 62.5 | Heart Math Freeze-Framer system 2.0 and Journey to the Wild Divine | Psycho-education exercises | 8 | NR | Changes in HRV and skin conductance level |
| Lehrer et al., (2000) | Children with asthma | $n = 20$ | $M = 12.4 \pm 3.4$ | 9–16 | 60 | KC-01 Cardiosignalizer | Relaxed abdominal pursed-lips breathing | 13–15 sessions | 20 min | / |
| McAusland and Addington (2018) | Young people at clinical high risk for developing psychosis | $n = 20$ | $M = 16.7 \pm 2.3$ | 13–22 | 30 | emWave 2 devices | Anxiety education | 4-week trial | Minimum 1 hr per week | / |
| Sowder et al., (2010) | Children with Functional Abdominal Pain (FAP) | Intervention group: $n = 20$; Control group: $n = 10$ | Intervention group: $M = 12.6 \pm 3.03$; Control group: $M = 14.4 \pm 2.86$ | 5–17 | Intervention group: 45; Control group: 50 | J&J Engineering I-330 C2 Portable 6-Channel Physiological Monitoring System | / | 6 | At least 10 min | Vagal tone; % of LF |
| Stern et al., (2014) | Children with Irritable Bowel Syndrome (IBS) and Functional Abdominal Pain (FAP) | Total: $n = 24$ (IBS: $n = 13$; FAP: $n = 11$) | IBS: $M = 10.69 \pm 3.4$; FAP: $M = 12.18 \pm 3.06$) | 6–17 | IBS: 46; FAP: 36 | J&J Engineering C2+ hardware and USE3 Software | / | Mean = 8 (between 3 and 18 sessions; stop when remission) | 30 min | HR and respiration rate |

ADHD, Attention-deficit hyperactivity disorder; DSM, Diagnostic and Statistical Manual of Mental Disorders; EEG, Electroencephalogram; HF, High frequency; HR, Heart rate; HRV, Heart rate variability; LF, Low frequency; NR, Not reported; QEEG, Quantitative electroencephalogram; RR intervals, intervals between successive heartbeats; SD, Standard deviation; VLF, Very low frequency.

Compared with controls, physiological measurements revealed that trained children had higher HRV levels during the recovery period, suggesting an increase in parasympathetic activity in response to stressful events.

The second study investigated the effect of a similar emotion self-regulation program (TestEdge) in a class of high-school students (mean age: 15 years old) on measures of test anxiety, socioemotional functions, test performance and HRV (Bradley et al., 2010). During this programme, students learned how to generate a psychophysiological state of coherence through HRV biofeedback exercises. A controlled preintervention and postintervention laboratory experiment using electrophysiological measures on a random stratified sample ($n$ = 136) was carried out to assess whether students were able to apply self-regulation techniques learned during the TestEdge program. Participants had to complete a computerized version of the Stroop test to simulate the stressful conditions of taking an academic test while several electrophysiological measures were recorded. Larger significant pre–post differences, showing reduced test anxiety and negative affect, and increased psychophysiological coherence after the intervention, were observed in the trained students group compared with controls. These findings suggest that they had learned how to better manage their emotions and regulate their psychophysiological activation level under stressful conditions.

Finally, a group of basketball and football adolescent and young adult players (aged between 16 and 21 years old) attended a series of HRV biofeedback training sessions to assess their benefits on their anxiety level and other psychophysiological parameters (Dziembowska et al., 2016). After 10 twenty-minute sessions, a significant decrease in the mean anxiety score was observed in the experimental group as well as improvements in their HRV measures, indicating better flexibility of their autonomic nervous system that could potentially lead to better athletic performance.

*HRV biofeedback in children and adolescents with physical and/or mental health disorders.* A first series of studies investigated the potential use of HRV biofeedback in addition to conventional pharmaceutical treatments to relieve pain in children. Using a case series design, Fahrenkamp and Benore (2019) reported changes in respiration rate and HRV in 4 adolescents with chronic pain (aged between 15 and 17 years old) who underwent a brief protocol of HRV biofeedback training (i.e. only 3 or 4 sessions). Postintervention results showed expected improvements in cardiopulmonary functioning and self-regulation abilities, supporting the benefits of using this type of technique, even for short periods, to improve pain management in paediatric populations with chronic pain. In the same vein, another study analysed archived data of 24 children and adolescents diagnosed with irritable bowel syndrome or functional abdominal pain (aged between 6 and 17 years old) to evaluate the clinical utility of HRV biofeedback in treating these conditions (Stern, Guiles, & Gevirtz, 2014). After completing approximately 8 thirty-minute sessions of HRV biofeedback, most participants reported partial or even complete remission. Confirming the interest of using HRV biofeedback to help children and adolescents manage pain, another study compared the regulatory performance of the autonomic system in a group of 20 children and adolescents with functional abdominal pain (aged between 5 and 17 years old) before and after 6 sessions of HRV biofeedback training (Sowder, Gevirtz, Shapiro, & Ebert, 2010). A comparison of baseline performance with a control group of healthy children and adolescents showed the presence of autonomic dysregulation (i.e. lower vagal tone) in participants who had functional abdominal pain. After the intervention programme, children and adolescents with functional pain demonstrated a significant reduction in pain frequency and intensity, and an increase in their autonomic balance. Taken together, these results seem to demonstrate the significant contribution of HRV biofeedback for this type of pathology, which, by improving the regulation of the autonomic system, enables children and adolescents to better manage their associated pain.

As the HRV biofeedback including guided breathing techniques is directly related to increased cardiopulmonary capacities, a case series study reported the results of 20 children and adolescents suffering from asthma (aged between 9 and 16 years old) who followed 13 to 15 biofeedback sessions coupled with an abdominal breathing protocol (i.e. Smetankin method; Lehrer, Smetankin, & Potapova, 2000). The preliminary uncontrolled results of this study showed mild improvement in two spirometric parameters after the protocol. Future larger-scale studies using this type of nonpharmacological intervention are needed to determine its usefulness for asthmatic children and adolescents.

Like pain management programmes, it has been suggested that attending biofeedback HRV sessions could be useful in helping children and adolescents to cope with stress and anxiety, whether these are generated by external events (such as medically invasive procedures; Shockey et al., 2013), are associated with other physical conditions (Slutsker, Konichezky, & Gothelf, 2010) or are one of the core symptoms of various mental health disorders (Kenien, 2015; Knox et al., 2011; McAusland & Addington, 2018; Pop-Jordanova, 2009; Thurstone & Lajoie, 2013). For example, children suffering from cancer undergo many painful and stressful invasive procedures. To determine whether HRV biofeedback could help them to cope, a 4-session intervention biofeedback coupled with relaxation was tested in a group of 12 children diagnosed with cancer (aged between 8 and 14 years old; Shockey et al., 2013). Compared with baseline, children after the biofeedback intervention reported a global decrease in their anxiety level and improvements in their HRV coherence scores were also observed, suggesting that these combined interventions may help children to manage their procedural distress. By addressing two pivotal aetiological factors, namely autonomic dysregulation and anticipatory anxiety, a case report study demonstrated the positive impact of HRV biofeedback in the treatment of a 13-year-old boy with cyclic vomiting syndrome not responding to medication (Slutsker et al., 2010). After 16 sessions combining psychoeducation, cognitive behavioural therapy and HRV biofeedback training, the patient had better HRV scores and was free of vomiting episodes even 4 months after the intervention.

Several studies have investigated the benefits of biofeedback HRV in groups of children and adolescents with mental health disorders specifically characterized by high levels of stress and anxiety. A group of 24 children and adolescents aged between 9 and 17 who were referred for treatment of anxiety were assigned to either a game-based biofeedback group or a waiting-list comparison group (Knox et al., 2011). The eight-session biofeedback intervention included psychoeducation and used computer-based gaming technology to teach and practise relaxation. Significant differences between the two groups were observed at post-test, the intervention group showing reduced anxiety and depression scores on standardized tests. Biofeedback-assisted relaxation training with a video game format thus appeared to be effective in reducing anxiety among children and adolescents. A similar HRV biofeedback intervention programme with a 4-week trial was proposed to a group of 20 adolescents and young adults (aged from 13 to 22 years old) at a clinically high risk of psychosis (McAusland & Addington, 2018). Postintervention results revealed significant changes in improving impaired tolerance to normal stress and dysphoric mood as well as in good overall adherence to treatment. However, no change in self-reported measures of anxiety and distress was observed. Although the effectiveness of the intervention was not fully established, HRV biofeedback constitutes a feasible treatment option to deal with anxiety symptoms in children and adolescents.

In another study, Pop-Jordanova (2009) attempted to evaluate the impact of biofeedback sessions on HRV level in some common mental health disorders in children (mean age: 12 years old). HRV changes were measured before and after the completion of 15 biofeedback training sessions of 16 min each, notably in children with anxious phobic symptoms ($n$ = 15), somatoform problems ($n$ = 15), obsessive–compulsive manifestations ($n$ = 7) or conduct disorders ($n$ = 12). Interestingly, biofeedback training had a positive impact on most groups, with maximum HRV changes observed in children with obsessive–compulsive, conduct and anxiety disorders. By using archival data, a recent study (Kenien, 2015) explored whether a self-induced state of coherence through HRV biofeedback specifically improved executive functions in a group of children (aged between 7 and 14 years old) with emotional disturbances. The intervention group ($n$ = 30) received 12 weeks of cardiac coherence training (20 sessions of 20 min), while the control group ($n$ = 30) did not receive any intervention. The children's executive functioning (i.e. inhibition, working memory, emotional control and shifting) was assessed on a scale (i.e. Behaviour Rating Inventory of Executive Function; Gioia, Isquith, Guy, & Kenworthy, 2000) by their teachers 1 week before and 1 week after the intervention. For both groups, no statistically significant improvements in the four executive processes evaluated were reported after the intervention, suggesting that HRV biofeedback training did not have a direct impact on the executive abilities of children with severe emotional disorders. Finally, a case study by Thurstone and Lajoie (2013) investigated the contribution of HRV biofeedback in improving the treatment of an adolescent with substance abuse problems. In addition to his cognitive behavioural therapy sessions, the 17-year-old teenager was also invited to attend 6 sessions of 10-min HRV biofeedback. While the preintervention patient's HRV tracing measures showed numerous irregularities, the postintervention results showed an improved amplitude and coherence level, reflecting better functioning of the parasympathetic nervous system. Furthermore, he also reported a significantly lower perceived level of stress than his baseline level, indicating that he felt calmer and more confident. These preliminary results are encouraging for the complementary use of this type of training to improve substance abuse treatment in young patients.

Finally, a series of studies investigated the benefits of HRV biofeedback in children and adolescents with developmental behavioural issues and/or learning disabilities. First, an uncontrolled experimental study compared the contribution of HRV biofeedback alone, as well as in combination with neurofeedback sessions, in a group of 15 children and adolescents with autism (aged between 9 and 18 years old; Goodman et al., 2018). The pre–post-intervention differences showed significant improvements in emotional regulation and social behaviours in all children and adolescents who received HRV biofeedback. In an attempt to find alternatives to classical pharmaceutical treatment, the benefit of therapeutic interventions including HRV biofeedback sessions has also been explored in several studies in children and adolescents with attention-deficit/hyperactivity disorder (ADHD; Amon & Campbell, 2008; Groeneveld et al., 2019; Lloyd, Brett, & Wesnes, 2010; Pop-Jordanova, 2009). In a retrospective study (Groeneveld et al., 2019), the results of behavioural and physiological preintervention and postintervention evaluations of 39 adults and 100 children and adolescents (aged between 6 and 17 years old) diagnosed with ADHD were compared. Participants benefited from a 30-min session of combined neurofeedback and HRV biofeedback. Physiological parameters changed significantly after treatment, and both statistically and clinically meaningful improvements in ADHD symptoms were observed, suggesting that this type of combined intervention holds promise for treating symptoms of ADHD. In a study investigating the contribution of HRV biofeedback in several groups of children with various mental health disorders, Pop-Jordanova (2009) included a group of children with ADHD ($n = 10$). However, after 15 training sessions, no significant change in physiological levels could be demonstrated in this group. Nevertheless, in two different controlled clinical trial studies (Amon & Campbell, 2008; Lloyd et al., 2010), HRV biofeedback therapy was also administered to children with ADHD (aged between 5 and 14). The first study focussed on the benefits of HRV biofeedback at behavioural level, measured by online questionnaires completed by parents at several phases of the intervention (i.e. preintervention, after 1 month, after 2 months and postintervention). The second study investigated both behavioural and cognitive changes induced by this type of intervention by evaluating children's performance. Together, these studies demonstrated significant improvements in both behaviour and cognitive functioning after the intervention, suggesting that therapy based on HRV biofeedback is beneficial in children with ADHD.

## Discussion

While it is widely and efficiently used in adults (for reviews, see Goessl et al., 2017; Lehrer et al., 2020), HRV biofeedback to improve stress and/or pain management in children and adolescents remains largely unexplored until now. The objective of this systematic review was to identify studies that have used HRV protocols either alone or in combination with other therapies, as well as to evaluate their usefulness and effectiveness in children and adolescents. Based on the findings, suggestions will be made to propose avenues for future research and to recommend clear and comprehensive guidelines for the clinical application of HRV biofeedback protocols in therapeutic interventions in order to obtain optimal results.

Overall, all 18 studies but one (Kenien, 2015) showed the positive contribution of HRV biofeedback sessions in children and adolescents. When effect sizes are reported by the authors, these are generally medium to large, suggesting the presence of robust effects. When they were implemented in a school or sports setting with healthy children (Bradley et al., 2010; Dziembowska et al., 2016; McCraty et al., 1999), the adaptation of physiological responses was better and with a lower level of test anxiety, suggesting that the emotional self-regulation capacities of the participants had improved. In a clinical context with children and adolescents who had physical and/or mental health disorders, HRV biofeedback helped to (a) improve several symptoms, (b) reduce disruptive behaviours, (c) enhance autonomic and emotional self-regulation, (d) reduce self-reported anxiety and pain levels, and (e) improve cognitive functioning. Children as young as 5 years old were able to synchronize their breathing rhythm, to understand the principles of biofeedback, and to learn to control the modulation of their physiological and emotional responses. Interestingly, positive results on stress and anxiety management are observed in children, adolescents and even young adults (Dziembowska et al., 2016; McAusland & Addington, 2018), suggesting that this type of technique is really suitable for individuals in a broad age group. In addition, they were able to reproduce the techniques and use them when faced with new stressful situations. Globally, this type of intervention appears to be easy to set up, even in a clinical or school context. Children and adolescents quickly learn the technique after a few coaching sessions, with positive behavioural and physiological consequences occurring very quickly, even after only a few sessions (e.g. 4 or 5 sessions; Fahrenkamp & Benore, 2019; Shockey et al., 2013). Finally, this type of intervention is cost-effective, totally safe and noninvasive, completely compatible and complementary with pharmaceutical or psychological treatments already set up, and the benefits seem to be generalized and long-lasting, with some changes still observed 6 months after the intervention ended.

While all these findings are very encouraging regarding the therapeutic potential of HRV biofeedback interventions, most of these studies suffered from significant methodological limitations, as demonstrated by the results of our quality assessment (Table S1). First, only 10 studies had a control group and matching with the experimental group on demographic data was not always performed. In most cases, the control group did not receive any intervention at all, with only one study using an active placebo (Lloyd et al., 2010) and one using a waiting list (Knox et al., 2011). Consequently, many observed benefits of HRV biofeedback interventions might be the consequence of uncontrolled factors. For example, the mere presence of an active intervention whatever its HRV content may have played a major role in promoting well-being and reducing stress. Second, most studies had limited sample sizes and very few used randomization to select their samples. Moreover, most studies have included in their sample participants in a broad age group, thus mixing children, adolescents and sometimes even young adults (Dziembowska et al., 2016; McAusland & Addington, 2018). The findings are therefore difficult to generalize, so larger, randomized, better-controlled studies are required. Third, while most studies used validated software and equipment to perform the HRV measurements and biofeedback sessions (often the emWave system developed by Heartmath), the protocols for applying the sessions differed greatly from one study to another. The number and duration of sessions varied, as did their frequency. Fourth, some studies used HRV biofeedback alone, while others combined it with relaxation or breathing exercises or even more traditional cognitive and behavioural therapy sessions. This lack of standardization of intervention protocols again hampers the generalization of the results and prevents the establishment of clear guidelines for clinicians using this technique. Moreover, when therapeutic approaches are combined, it is no longer possible to identify the respective impact of each intervention, and the contribution of HRV biofeedback in particular. Finally, to demonstrate the impact of HRV biofeedback, preintervention and postintervention measures were compared. These measures consisted mostly of self-reported questionnaires, with a few studies also using observations provided by parents and teachers. Only one study included more objective and less biased measures (i.e. neuropsychological standardized tests; Lloyd et al., 2010), particularly to quantify the modulation of cognitive functions, and not all studies confirmed through real-time physiological measurements that biofeedback had a direct impact on the level of HRV.

Considering all these limitations, future experimental studies should adopt better-defined and controlled protocols to confirm definitively and validly the efficiency of HRV biofeedback in children and adolescents. Future studies should, therefore, include larger samples selected using conventional randomization methods, and an active control group matched at baseline for relevant variables, ideally with a staggered schedule including them in a waiting list system, or with other alternative placebo interventions. Including more restricted age groups in future studies would also allow the impact of HRV biofeedback to be more precisely defined and differentiated according to age. Precise, standardized physiological measurements during biofeedback sessions should be performed to ensure that children and adolescents are adherent and sensitive to this type of intervention. In addition, more objective and quantitative measurements (e.g. neuropsychological tests, experimental tasks), not just self-reported ones, should be used to confirm the beneficial effects of biofeedback sessions on cognitive and affective functioning. Finally, if HRV biofeedback is applied in combination with other therapeutic approaches (e.g. relaxation, cognitive behavioural therapy), it will be important to include control groups receiving each of the approaches individually, in addition to the group receiving the multiple approaches, in order to isolate the specific effects of each intervention.

Although experimental validation remains necessary, the promising results observed following the use of HRV biofeedback in the various studies identified in this systematic review prompt us to formulate a series of clinical recommendations representing the foundations of future guidelines to be applied systematically for the use of this type of intervention with children and adolescents. Firstly, who can benefit from HRV biofeedback interventions? As demonstrated in the selected studies, children from 5 years old can benefit from this type of session. Adolescents are also positively receptive to this type of intervention. Interestingly, HRV biofeedback can have positive consequences both for healthy children/adolescents and children/adolescents with physical and/or mental health disorders. When HRV biofeedback is applied in a clinical setting, it has been shown to improve stress and concentration regulation in patients suffering from either anxiety and emotional disorders (e.g. phobia, psychosis) or behavioural and learning disorders (e.g. ADHD, autism). In addition, it can also help in the management of anxiety and/or pain induced by other physical pathologies requiring frequent and invasive tests or interventions (e.g. cancer, functional abdominal pain). Secondly, how can HRV biofeedback be optimally applied? To achieve significant positive effects, the various studies used a protocol with an average of 6 to 15 sessions, at a rate of 1 to 2 sessions per week. Each session lasted about 20 min and was often accompanied by breathing and/or relaxation exercises, as well as psycho-educational advice. Equipped with an HRV sensor, children or adolescents could generally visualize their physiological parameters on a computer screen and learn how to modulate them through video game-based exercises. In addition to arousing children's and adolescents' interest and giving a playful aspect to the breathing exercise, the use of this type of video game seems to promote the learning of regulation techniques and improve compliance with treatment. Furthermore, studies have reported the presence of even greater benefits when children and adolescents tend to do breathing exercise naturally at home and parents fully participate in the intervention programme by doing exercise with their children (e.g. Goodman et al., 2018; Sowder et al., 2010). Allowing children and adolescents to undergo virtual HRV biofeedback training sessions, particularly in the current global health context related to the COVID-19 pandemic, therefore appears to be a useful and appropriate way to help them to cope with daily stressors. Finally, in a clinical context, we advise proposing HRV biofeedback interventions in combination with more traditional drug and/or therapeutic treatments. HRV biofeedback sessions are not time-consuming and do not have any disruptive effects, making them an ideal complement to other therapeutic approaches.

In conclusion, this systematic review demonstrates the feasibility of HRV biofeedback interventions in children and adolescents and highlights the substantial benefits provided by it on a variety of physical, behavioural and cognitive problems. Although methodological limitations have been identified requiring replication of these results in more controlled experimental studies, the promising results observed to date pave the way for this type of intervention in clinical and/or school settings. The development of integrated portable solutions combining biofeedback on physiological parameters and breathing exercises, and allowing easy and autonomous use by children and adolescents wherever and whenever they wish, would be a most appreciable objective in the short and midterm.

## Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article:

**Appendix S1** Questions related to each item.

**Table S1**. Comparison group studies scoring using adapted quality assessment tool for controlled intervention studies (NHLBI, 2014)


## Acknowledgements

N.V. is a senior research associate at the Fund for Scientific Research (F.R.S.-FNRS, Belgium). V.D. is funded by the Service public de Wallonie – Économie, Emploi, Recherche (SPWEER, Belgium). This work is the result of the Focus project which was supported and financed by the ‘Maison Européenne des Sciences de l’Homme et de la Société’, the State and the Hauts-de-France Regional Council within the framework of the CPER ISI-MESHS. The authors have declared that they have no competing or potential conflicts of interest.



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## Key Points

- Heart rate variability biofeedback is useful to manage stress and pain in adults.
- However, its use and health benefits in children and adolescents have received little attention.
- Despite several methodological weaknesses, findings showed the potential therapeutic values of using HRV biofeedback in these populations.
- We propose evidence-based guidelines for its upcoming clinical application.

**Note**

1. Although explicitly including children and adolescents in their sample, it is important to note that two studies (Dziembowska et al., 2016; McAusland and Addington, 2018) included a wide age range participants, up to 21 and 22 years old, respectively. As part of the sample consists of young adults, it is important to be cautious about drawing conclusions regarding the specific efficiency of this type of HRV intervention for children and adolescents.

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Accepted for publication: 3 May 2021