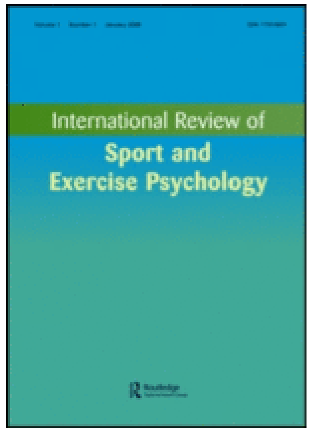


# A Scoping Review of Heart Rate Variability in Sport and Exercise Psychology: Guidance for Best Practice



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# A Scoping Review of Heart Rate Variability in Sport and Exercise Psychology

## Abstract

Sport and Exercise Psychology (SEP) often adopts physiological markers in theory and practice, and one measure receiving increasing attention is heart rate variability (HRV). This paper aimed to provide a scoping review of the use of HRV within SEP. The protocol was made available on the Open Science Framework. Study inclusion criteria were examination of HRV in SEP, using athletes or healthy populations, peer-reviewed and published in English. Exclusion criteria were non-peer reviewed work, animal studies, clinical populations, review or conference papers. In February 2022 a systematic search of Web of Science, PubMed and Sport Discus identified 118 studies (4979 participants) using HRV in sport psychology (71) or exercise psychology (47). Risk of bias was assessed via the Mixed Methods Appraisal Tool. A narrative synthesis revealed that HRV was assessed within a range of topics such as stress, overtraining, anxiety, biofeedback, cognitive performance, and sporting performance. Three key limitations within the field were discovered: limited application of theoretical frameworks, methodological issues with HRV measurement, and differing interpretations of HRV results. Future research should use vagally-mediated HRV as a marker of self-regulation and adaptation in SEP, consult relevant HRV theories prior to hypothesis development, and follow methodological guidelines for HRV.


Word Count: 9,885

Keywords: physical activity; cardiac vagal activity; vagus nerve; parasympathetic activity, sympathetic activity

## Introduction

Sport and exercise psychology (SEP) is a continuously evolving area. Traditionally, research and practice in SEP explores many concepts that are subjective in nature (e.g., what is an athlete's motivation, how does exercise make people feel). Hence, a large proportion of the measurement in SEP has been based on self-report instruments (Duda, 1998). While self-report instruments do provide valuable information for SEP, it is increasingly acknowledged that psychophysiological evidence can support, extend and develop SEP theory and practice (e.g., Cooke & Ring, 2019; Hoffmann et al., 2018; Lautenbach & Lobinger, 2018; Meijen et al., 2020). One measure of growing interest is heart rate variability (HRV), which represents the change in the time intervals between adjacent heartbeats (Akselrod et al., 1981; Berntson et al., 1997; Camm, 1996; Laborde et al., 2017).

HRV use has been increasing for several reasons. First, it reflects psychophysiological phenomena related to self-regulation and health (Smith et al., 2017; Thayer et al., 2009). Self-regulation is defined as a system of standards, thoughts, processes, and actions that direct individual's behaviour toward desired end states (Carver and Scheier, 2012). Health is defined as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" (WHO, 2022, point 1). Both self-regulation and health are of interest to be indexed and understood within SEP phenomena. Second, HRV is non-invasive, easy to use and a relatively cheap physiological measure, making it accessible to researchers and practitioners in SEP. However, this often masks the complexities around the theoretical understanding and the interpretation of HRV data. HRV has been reviewed in several fields to understand elements of human function (e.g. monitoring military personnel [Hinde et al. 2021], mental workload [Lean & Shan, 2011], workplace stress [Jarczok et al., 2013]). Within SEP, although there have been context specific efforts to synthesize the HRV literature, for example with a focus on HRV biofeedback (an intervention where participants get live physiological feedback such as heart rate, HRV, or respiratory frequency during slow-paced breathing) (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021), there has been no holistic overview of HRV use. Therefore, the aim of this scoping review is to collate the current use of HRV in SEP and to delineate future directions and recommendations for researchers.

HRV reflects the autonomic nervous system functioning (Berntson et al., 1997; Camm, 1996; Kreibig, 2010). This variation in beat-to-beat intervals can be seen as an emergent property of interdependent regulatory systems that operate on different time scales to adapt the organism to challenges and allow achieving goal directed behaviour (Thayer et al., 2012). This premise alone is very attractive to SEP given adaptation to varying environments is a crucial element of performance and wellbeing (Thayer et al., 2009; Raab et al., 2015). Regarding the physiological mechanisms underlying HRV, previous positions suggested that both sympathetic and parasympathetic nervous activity could be identified through its measurement. Claims regarding HRV reflecting sympathetic activity or the "sympatho-vagal balance" are generally rejected by researchers (Ackermann et al., 2021; Berntson et al., 2008; Billman, 2013; Eckberg, 1997; Heathers, 2012; Malliani et al., 1998). This is because the "sympatho-vagal balance" is argued to be calculated with the LF/HF ratio. In contrast to initial thinking, it has now been shown that low frequency HRV is not a reliable indicator of sympathetic nervous activity (Ackermann et al., 2021; Goldstein et al., 2011; Rahman et al., 2011). Consequently, the sympatho-vagal balance as measured by the LF/HF ratio is an inaccurate conceptualization (Billman, 2013; Heathers, 2012)"

Hence, there has been a shift towards focussing the interpretation of HRV in relation to parasympathetic nervous activity (Laborde et al., 2017). Parasympathetic nervous activity is often referred to as vagal activity, given its primary afferences come from the 10$^{th}$ cranial nerve, also known as the vagus nerve (Brodal, 2016; Shaffer et al., 2014). HRV indexes the activity of the vagus nerve regulating cardiac function, termed cardiac vagal activity or cardiac vagal tone (Laborde et al., 2017). The HRV parameters suggested to reflect cardiac vagal activity are referred to as vagally-mediated HRV (vmHRV).

There are five theories which provide predictions for the role of cardiac vagal activity within human function (for an overview of HRV theories, see Laborde et al., 2017; Shaffer et al., 2014). These are the polyvagal theory (Porges, 1995), the neurovisceral integration model (Thayer et al., 2009), the psychophysiological coherence model (McCraty & Childre, 2010; McCraty & Zayas, 2014), the resonance frequency model (Lehrer, 2013), and the vagal tank theory (Laborde et al., 2018). As detailing each of these theories is outside the scope of this review, we provide an overview in Table 1. Overall, these theories highlight that vmHRV indexes psychophysiological processes of interest within SEP.

INSERT TABLE 1 AROUND HERE

Applications of HRV within SEP encompasses various areas, for example research about executive functions in athletes (e.g., Mosley et al., 2018a), the link between physical fitness and cognitive processing (e.g., Dupuy et al., 2018), or interventions such as HRV biofeedback (e.g., Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2021) or examining self-regulatory adaptations during both internal (negative imagery) and external (negative crowd noise) demands (e.g., Laborde et al., 2011). To date, there has been no holistic overview of how HRV is utilised within SEP, despite it having many applications of interest in this field. Based on this, it is no surprise that HRV's use has grown exponentially within the SEP domain, specifically in the past twenty years (see Figure 1). This growth is most likely linked to the ease of data collection for HRV and the fact that technologies are becoming far more accessible and affordable. In addition, advances in SEP research and practice have been shifting towards understanding psychological processes together with physiological measures (Cooke & Ring, 2019).

INSERT FIGURE 1 AROUND HERE

With this surge in research interest and accessible technology comes a need for standardization and methodological rigour when using HRV in SEP. There have been recent developments within methodological guidelines, effective experimentation, and measurement of HRV (Catai et al., 2020; Laborde et al., 2017; Quintana et al., 2016; Quintana & Heathers, 2014). However, these are still emerging, inconsistently applied and often researchers use previously published studies containing conceptual and methodological flaws. Researchers using past papers to inform the preparation of their research projects can lead to incorrect practice, consequently a synthesis of these methodological aspects in SEP research is of the upmost importance. There are three key methodological areas that should be considered when planning, collecting, and interpreting HRV: HRV measurement times, HRV measurement device, and HRV parameters. We direct the reader to Table 2 (a,b,c) and Figure 2 in which we highlight key methodological considerations for HRV research.

INSERT TABLE 2 (A, B, C) AND FIGURE 2 AROUND HERE

Previous evidence of the research conducted in SEP shows a diversity of topics investigated together with HRV, such as anxiety or stress, but an overarching synthesis of HRV use in SEP is missing in current literature. In addition, some of the work within HRV in SEP has differing methodologies and parameters reported. A scoping review presents itself as a timely endeavour to synthesize the evidence in the field in line with methodological guidelines to determine the quality of the results and generalizability of the findings within SEP. Without the correct application of theory and methodology, HRV findings can be questioned and therefore wrongly inform the SEP audience and future research. The concept of this scoping review was consequently to determine how HRV is being used within SEP research. Within this we aim to provide an overview of the phenomena studied, together with discussion of the theories underlying the studies as well as a critical appraisal of the methodology used, investigating the extent of standardization of procedures, to enable a meaningful interpretation of the findings in the context of SEP.

## Methodology

### *Scoping review*

Scoping reviews aim to establish the coverage of a body of literature within a given topic, provide an indication of the amount of literature, and give a broad overview of its focus (Munn et al., 2018). This review was deemed to be a scoping review due to the broad aim (to determine how HRV has been used in SEP research) and due to its focus on the application of HRV methods within SEP literature.

### *Pre-registration*

The study's methodology was made publicly available on the Open Science Framework on August 13th, 2020, and can be accessed online (https://osf.io/u7g5v). For transparency the initial search took place prior to pre-registration, which is reported in the pre-registration file. The search criteria and inclusion/exclusion criteria have not changed at any point, some additional examples have been added in the manuscript for further clarity. In addition, it was decided during the peer review process to label the review a scoping review rather than a systematic review.

### *Conceptualising search area*

To develop a clear search strategy, the authors first defined the areas of interest to the scoping review, as findings will be reported separately in the results. Sport psychology involves the application of theories, principles, and techniques from mainstream psychology to foster psycho-behavioural change in athletic populations to enhance performance, the quality of the sport experience, and personal growth of the athlete (Vealey, 1994). Within this review, sports were deemed to be institutionalised environments involving physical exertion, complex physical skills, and rules that exist as a result of organisation (Pink, 2008). Exercise psychology is defined as "the application of psychology to antecedents and consequences of health-related physical activity" (Biddle & Fuchs, 2009, p. 410). Biddle and Fuchs (2009) also provide three main themes of exercise psychology: 1. Psychological antecedents of health-related physical activity (e.g., self-efficacy, motivation etc.), 2. Psychological constructs that may change physical activity and their use in intervention, and 3. Psychological consequences of physical activity (e.g., a change in cognitive function as a result of exercise).

**Search strategy**

An extensive electronic search was conducted to identify all empirical studies including HRV within sport psychology and exercise psychology. Following the PRISMA statement guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009; Page et al., 2021), a systematic search of databases was conducted within Web of Science, PubMed and Sport Discuss. The final search was conducted in February 2022 (09.02.2022). The search terms used in this review were as follows: "Heart rate variability" OR "HRV" OR "Parasympathetic" OR "Vagal" OR "Vagus" AND "Sport" OR "Exercise" OR "Physical activity".

**Inclusion and exclusion criteria**

To ensure a thorough review, inclusion and exclusion criteria were developed. The inclusion criteria were as follows: (a) the study was empirical in nature, (b) examined HRV in conjunction with psychology in sport, exercise, or physical activity domains, (c) assessed athletes at any competitive level within sport or healthy populations within exercise, (d) and had undergone peer review to be published within an English language journal or book. Exclusion criteria included: (e) non-peer-reviewed work such as doctoral dissertations, (f) animal studies, (g) populations with a clinical illness, (h) and review papers or conference papers. For further clarity on inclusion and exclusion criteria see Supplementary Material 1.

**Sifting Resources**

In line with the PRISMA guidelines, a detailed record of the screening process was kept (see Figure 3). The total number of items screened was 15466, which was the total from all three databases (Web of Science: 8160, Pub Med: 5330 and Sport Discus: 1976). Duplicates were then removed via automatic detection on EndNote Desktop which removed 6871 articles, duplicates were then manually screened which removed an additional 1157 articles[1]. 7438 articles remained to be assessed via title and abstract, from which irrelevant topics were removed.

The full text of the remaining 195 articles were then read to assess eligibility. On completion of this process, the two authors checked the selected studies regarding inclusion criteria. They then discussed any studies whose inclusion was unclear in relation to the set criteria (n = 6). These discrepancies can be seen in Supplementary Material 2, in which two of the six studies were included. There were no further discrepancies in this process.

All included papers had both reference lists and citations (using the citation function of Google Scholar) manually searched, this retrieved 25 papers (reference lists = 16, citations = 9). As a final stage, all first authors of included studies were emailed to determine if they had any upcoming work or any other relevant papers. The authors were given a deadline to respond, this process added 2 papers. This totalled 118 texts being included within the review, for the full PRISMA flow diagram of this process, see Figure 3, and for the PRISMA checklist, see Supplementary Material 3.

INSERT FIGURE 3 AROUND HERE

[1] Note: EndNote automatic duplicate removal does not take into account differences in capitalisation of titles or differences in author name presentation, which provided a large number of manual duplicates as a result.

***Data extraction and synthesis***

The 118 papers retrieved from the systematic process were then split into either sport psychology (71) or exercise psychology (47) related papers (presented in Table 3 and 4). Instead of using the PICOS guidelines, given that we did not directly assess intervention-based research, we extracted the following information from the included papers: authors, participants, protocol, HRV measurement, HRV indices presented, main findings. We deemed these the most important when using HRV data, given the sensitivity of the measure and its interpretation (Berntson et al., 1997; Laborde et al., 2017; Quintana et al., 2016; Quintana & Heathers, 2014; Shaffer & Ginsberg, 2017).

The main findings from each study were amalgamated through a narrative synthesis (Siddaway et al., 2019), which is a method often used when the characteristics of the studies are too disparate and therefore cannot provide a meaningful summary of effect (Brennan, 2009). Popay and colleagues (2006) define narrative synthesis as a process that "relies primarily on the use of words and text to summarise and explain the findings of the synthesis" (p. 5). Where possible the authors followed the Synthesis Without Meta-Analysis (SWiM) guidelines, which were developed to address shortcomings in narrative synthesis in systematic reviews (Campbell et al., 2020), see Supplementary Material 4. The decision to compile the data in this way rather than performing a meta-analysis was due to the heterogeneity of the studies including differences in study design, the absence of focus on interventions, the range of HRV parameters used, and the range of differing outcome measures.

***Risk of Bias Assessment***

To assess the risk of bias across such a wide and diverse range of studies, we used the Mixed Methods Appraisal Tool (Hong et al., 2018). Each study was screened against seven risk of bias questions, which were dependant on study design, and this was completed by the two authors. Example items include: “Are there clear research questions?” And “Do the collected data allow to address the research questions?". Studies were answered as yes, no, can't tell or not applicable, there were no discrepancies between the authors and the full table for the risk of bias assessment can be found in Table 5.

## Results

### *Study Description*

The 118 papers retrieved from the systematic process yielded 71 sport psychology papers and 47 exercise psychology papers, with a total of 4979 participants. Key biases in the literature mainly emerged from not controlling for confounding variables that influence HRV such as age. The full table for the risk of bias assessment can be found in Table 5. For this review, due to the importance of HRV measurement and parameter selection, we have chosen to report three areas of interest around study description: 1. HRV measurement times, 2. HRV measurement device, and 3. HRV parameters.

### *HRV Measurement Times*

The most common measurement of HRV was resting baseline with 112 of the 118 studies reporting it (94.9%). This is unsurprising, given one of the most accepted theoretical models within the literature, the neurovisceral integration model (Thayer et al., 2009), uses resting baseline HRV as the key predictor of self-regulation, wellbeing, and health. Event (n = 48, 40.6%) and post-event HRV (n = 34, 28.8%) was not measured as often as resting. Very limited research in SEP examined the role of reactivity (n = 12, 10.6%) and recovery (n = 9, 7.6%).

### *HRV Measurement Device*

HRV can be collected in three main ways[2] (Supplementary Material 2b), multi-lead ECG devices (n = 54), chest belt ECG (n = 53), devices based on PPG (n = 12), and unknown

[2] Note: two studies reported using two different devices (Frenkel et al., 2019; Gross et al., 2017)

(n = 1). The most frequently used branded devices were Polar chest belts (n = 43) and 36.4% studies reported using a version of this brand, which is unsurprising given their accessible and affordable nature. Following Polar, the most frequently used devices were the Procomp infini (n =11, 9.3 %), eMotion Faros (n = 8, 5.9%), Nexus (n = 7, 5.9%), and Suunto (n = 4, 3.3%). Other studies tended to use devices able to collect ECG (e.g., Amlab Physiograph, Model 1.7) or other devices that are available within the consumer market, such as Hexoskin (n = 2), emWave (n = 2), iThlete (n = 1), Firstbeat (n = 1), and HRV4Training (n = 1).

***HRV Parameters Reported***

Across all studies, the most commonly reported parameter was RMSSD (n = 59) followed by the LF/HF ratio (n = 48, 58 when all LF/HF parameters were grouped: LF/HF n = 48, LF/HFnu n = 5, LF/HF% n = 3, LF/HFms$^2$ n = 2). Figure 4 shows the frequency of parameters reported.

INSERT FIGURE 4 AROUND HERE

***Narrative Synthesis***

Throughout the narrative analysis we highlight the differences in parameters reported. Vagally-mediated HRV is reported as vmHRV, followed by the parameter that reflects vmHRV in parentheses (RMSSD, HFms$^2$, pNN50, SD1, RSA). When the parameter reported is not vagally mediated, it is reported as HRV (parameter name), e.g., HRV (SDNN), and if the measurement units of the frequency domain parameters are not specified, then it is reported as "unit not specified" (uns): e.g., HRV (HFuns).

***Sport Psychology***

*Psychological Stress*

HRV is often associated to the stress response due to its links with the autonomic nervous system, and in particular the parasympathetic nervous system (Laborde et al., 2017; Thayer et al., 2009). It is important to note that there are limitations to indexing stress with HRV, which are highlighted in the discussion. HRV has been used to examine the response to competitive stress and often lower levels of HRV are observed in the lead up to competition, for vmHRV (pNN50) and HRV (HF%) (Sartor et al., 2017; D'Ascenzi et al., 2014). However, when comparing a training day and a competitive selection day, there were no differences in vmHRV (HFms$^2$) or HRV (LF ms$^2$) (Iellamo, 2003). Longitudinally (season of competitive soccer) HRV (HFnu) decreased from pre to post season whereas HRV (LFnu, LF/HF) increased, but mixed results existed regarding relationships between subjective stress ratings and HRV parameters (Morales et al., 2019). When competition stress was controlled for (stress ratings out of competitive season) those with lower perceived stress had higher vmHRV (Mamlouk et al., 2021).

HRV has also been investigated with laboratory induced stressors in athletes. Lower vmHRV is often linked to the onset of stress, for example lower HFms$^2$ during a cold pressor task (Britton et al., 2019), lower RMSSD during a climbing task (Frenkel et al., 2019) and lower RMSSD and pNN50 during a psychological stress test (Móra et al., 2022). During simulated competitive stress, a significant increase in HRV (LF/HF) was observed in handball players (Laborde et al., 2011). In another laboratory study asking participants to recall a sporting failure, athletes who had higher self-compassion had an increase in HRV (HFuns) from baseline to the onset of stress (Ceccarelli et al., 2019). Intervention strategies used HRV as a measure of stress to determine their effectiveness, for example a yoga intervention was found to decrease HRV (LF/HF) (Patil et al., 2013), while a mindfulness-based intervention found no influence on vmHRV (SD1) or HRV (SD2) (Ceccarelli et al., 2019; Holguín-Ramírez et al., 2020). Overall relationships between stress and HRV are mixed and are often challenging to interpret based on the nature of the stressor.

*Precompetitive Anxiety*

HRV is also often used as a marker of precompetitive anxiety, and it has been examined across different competitive scenarios. A popular paradigm often compares training or simulated competitive scenarios with real competition (Cervantes Blásquez, 2009; Morales et al., 2013). In real competition, anxiety has been associated with decreased vmHRV: pNN50, RMSSD, HFms$^2$, SD1 (Ayuso-Moreno et al., 2020), RMSSD, SD1, HFms$^2$ (Cervantes Blásquez, 2009), RMSSD, pNN50, SD1, HFms$^2$ (Morales et al., 2013), RMSSD (Mateo et al., 2012), and increased HRV (LF/HF) (Cervantes Blásquez, 2009; Mateo et al., 2012; Parrado et al., 2010). Specific relationships were also noted, for example a negative relationship between vmHRV (RMSSD) and somatic anxiety (Fortes, 2017; Morales et al., 2013), and between vmHRV (RMSSD) and cognitive anxiety (Fortes, 2017). Ortigosa-Marquez and colleagues (2017) found that anxiety (measured via the Profile of Mood States) was negatively correlated with HRV (HFuns) but positively corelated with HRV (VLFuns). Contrary to these findings, other studies found no relationship between perceived anxiety and HRV parameters prior to competition: vmHRV (RMSSD, SD1) (Oliveira-Silva et al., 2018), HRV (LF/HF) (Souza et al., 2019), and HRV (HRV coherence) (Paula Jr, 2016). As with stress, the links between HRV and precompetitive anxiety are still unclear.

*Cognitive Function*

There are well established theoretical links between executive functioning and vmHRV (Smith et al., 2017; Thayer et al., 2009), and cognitive performance emerged as an important topic area. Master athletes showed greater dual task performance when compared to a lower fit control, and this performance was mediated by vmHRV (RMSSD, SD1) and HRV (HFnu) (Dupuy et al., 2018). Further, athletes who performed better during a working memory task had lower vmHRV (HFms$^2$) (Mosley et al., 2018a). However, no relationship was found between Stroop performance and HRV (HF%) and vmHRV (pNN50) (Sartor et al., 2017), or vmHRV (RMSSD, pNN50) and HRV (SDNN) (Gantois et al., 2020).

Executive performance has also been assessed in stressed, overreached, and injured athletes. Jockeys who had higher HRV (LF/HF) ratios had impaired decision making during a high stress period (Landolt et al., 2017). In overreached and overtrained athletes, poorer Stroop performance was not linked to vmHRV (RMSSD, HFms$^2$) (Dupuy et al., 2014; Hynynen et al., 2008) or HRV (TPms$^2$, LFms$^2$) (Hynynen et al., 2008). In concussed athletes, vmHRV (HFms$^2$) was lower at rest but was increased during a cognitive 2-Back task measuring sustained attention (Huang et al., 2019). Other applications linked to cognitive effort (HRV as a measure of attentional load) found elite golfers had lower HRV (LFms$^2$) during a putting task in comparison to novice golfers (Neumann & Thomas, 2009). Overall, there are mixed findings within cognitive performance and HRV, and the relationships observed between executive functioning and vmHRV did not always follow the predictions of the neurovisceral integration model (Thayer et al., 2009, see Table 1).

*HRV-Biofeedback*

HRV biofeedback refers to combining slow-paced breathing with a visualization of heart rate, HRV, and/or sometimes the respiration signal, to improve its effectiveness (Laborde et al., 2021; Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Shaffer & Meehan, 2020). Its primary target is to stimulate the vagus nerve (Sevoz-Couche & Laborde, 2022), reflected in increases in vagally-mediated HRV (Laborde et al., 2022), which then impact a large range of self-regulatory phenomena (Lehrer et al., 2020). HRV biofeedback has already been reviewed in the literature, and we direct the interested reader to systematic reviews and meta-analyses by Pagaduan, Chen, Fell and Wu (2021), Pagaduan, Chen, Fell and Wu (2020), and Jiménez-Morgan and Mora (2017). Differences on HRV and vmHRV emerged when comparing length of intervention as HRV is often increased, specifically in vmHRV (HFms$^2$) (Lagos, 2008; Paul et al., 2012) and HRV (HFuns) (Park et al., 2020), HRV (SDNN) (Ortega & Wang, 2018a; Park et al., 2020), HRV (LFuns) (Park et al., 2020) and HRV (LFms$^2$) (Rollo et al., 2017). However, in short-term (single session) breathing interventions, without biofeedback, effects in vmHRV (RMSSD) were found to dissipate after slow-paced breathing ends (You et al., 2021). In addition, not all studies involving HRV biofeedback intervention have found changes in HRV (e.g., Shaw et al., 2012). Finally, when comparing slow-paced breathing without biofeedback to other relaxation techniques, it has been found to be more effective at increasing HRV (SDNN) than progressive muscular relaxation (Hunt et al., 2018), and at increasing vmHRV (RMSSD) during a single slow-paced breathing session (You et al., 2021a; You et al., 2021b), than watching a neutral documentary (You et al., 2021a) or resting control (You et al., 2021b). Although HRV-biofeedback can positively influence performance, anxiety, HRV and vmHRV, more exploration around duration and type of intervention is needed.

*Recovery, Overtraining and Injury*

HRV is commonly used within the training science community as a marker of overtraining and physical recovery. Studies have shown that subjective indicators of better recovery (e.g., increased vigor, lower perceived tiredness) is positively related to vmHRV in a range of sports including swimming, with RMSSD (Flatt et al., 2017) and pNN50 (Vacher et al., 2018), hockey (RMSSD and pNN50) (Parrado et al., 2010), and HRV (lnHFnu) in badminton (Bisschoff, 2016). In swimmers wellbeing variables improved the predicted variance of vmHRV (RMSSD) in addition to training load (Piatrikova et al., 2021). However, this is not always the case, and some conflicting results exist with vmHRV and subjective indicators of recovery, for example a positive relationship between higher total mood disturbance and vmHRV ($HFms^2$) in rugby players (Yen, 2012). Additionally, several studies found no relationship between vmHRV and subjective indicators of recovery and overtraining: RMSSD (Dobson et al., 2020; Nicolas et al., 2019), lnRMSSD (Botonis et al., 2021; Tibana et al., 2019), RMSSD and pNN50 (Hauer et al., 2020), and RMSSD, $HFms^2$, pNN50, SD1 (Portillo & Rodríguez, 2020).

Overtraining and injury have also been examined with HRV in a psychological context. In a study examining concussed athletes, total mood disturbance was linked to a decrease in

LFms² (Hutchison et al., 2017) and overtrained athletes had a lack of reactivity in vmHRV (HFms², RMSSD) and HRV (TPms², LF) during a Stroop task (Hynynen et al., 2008). Current findings for vmHRV, overtraining and subjective psychological parameters are consequently mixed.

*Challenge and threat*

HRV is often used with self-report measures to help further understand psychological processes such as appraisal. Thus, HRV has been used in line with challenge and threat states. Thornton, Sheffield and Baird (2019) found that when comparing experienced and novice contact sport athletes (such as rugby) and non-contact athletes experiencing pain, experienced contact athletes were more challenged and had higher vmHRV (RMSSD). When comparing across all athletes regardless of sport type, those who perceived events as more challenging also had higher vmHRV (RMSSD) (Thornton et al., 2019). In a laboratory study, greater threat appraisal was negatively related to HRV (HFnu) in athletes both during the task and while considering the reactivity from baseline (Laborde et al., 2015). Although only limited relationships have been found within HRV and challenge and threat states, HRV may be an additional cardiac indicator of interest within challenge and threat.

*Pain*

HRV has been assessed in line with pain measurements to understand its relationship with subjective ratings of pain during pain tasks. Across the majority of studies, athletes who report greater experiences of pain or who had higher pain catastrophizing often have stronger cardiovascular reactions during cold pressor tasks such as increased HRV (SDNN) (Matylda et al., 2020) and decreased vmHRV (HFms²) (Britton et al., 2019). Whereas athletes who tend to experience pain more often, in this study experienced contact athletes had higher vmHRV (RMSSD) when experiencing pain (Thornton et al., 2019). In summary, HRV is showing promise as a psychophysiological indicator of pain, given both the experience of pain and the perception of pain is associated to vmHRV.

*Personality traits*

HRV has also been assessed with personality measures to help understand how personality traits might influence athletes' reactions to the sporting environment. Handball players who had higher trait emotional intelligence had lower HRV (LF/HF) when faced with a stressor (Laborde et al., 2011). Trait emotional intelligence was also linked to higher baseline HRV (HFnu) in athletes (Laborde et al., 2015). Movement reinvestment was also found to be associated to increased vmHRV ($HFms^2$) recovery in athletes after a dart throwing task (Mosley et al., 2017). Similarly, higher trait emotional intelligence (self-control) had higher vmHRV ($HFms^2$) during a pressurised shooting task (Mosley et al., 2018b). Initial findings suggest there may be relationships between trait-based measures and HRV, however more investigation is needed.

*Motivation*

In a study examining different types of need achievement motivation and the connection to psychophysiological states in wrestling athletes, no relationship was found between HRV parameters and motivation (Korobeynikov, 2011). A study investigating the role of visual primes on situational motivation and activation found that manipulating athletes' emotional and psychophysiological states via priming pre-exercise (through video-music conditions) resulted in an increase in HRV (LFuns) and a decrease in HRV (HFuns) (Loizou & Karageorghis, 2015). Limited investigations have taken place with regards to motivation and HRV, and current findings are mixed.

*Mood*

Mood has been linked to HRV with mixed findings. Anxiety and confusion (measured via the Profile of Mood States) were inversely correlated with HRV (lnHFuns) and HRV (lnVLF) was positively correlated with anxiety and negatively correlated with vigor (Ortigosa-Márquez et al., 2017). However, most studies found no relationship between mood markers, HRV and vmHRV (Paula Jr, 2016; Vaz et al., 2019; Yen, 2012), therefore limited conclusions can be drawn between HRV and mood.

*Flow*

Flow is often linked to optimal links between body and mind in sport and therefore Kim, Hwang, Park, Cho, and Kim (2019) examined flow, shooting performance and HRV. No relationship was found between flow and vmHRV (RMSSD, $HFms^2$) or HRV (SDNN, $LFms^2$, LF/HF), although HRV (LF/HF) was significantly lower at rest when compared to practice and actual shooting. As only one study examined the relationship between flow and HRV, more investigation is needed.

*Self-efficacy and self confidence*

Self-efficacy and shooting performance were compared with vmHRV and it was found self-efficacy and shooting score were positively correlated with vmHRV (RMSSD) (Ortega & Wang, 2018b). Self-confidence was also found to have a positive relationship with vmHRV (RMSSD, pNN50) and HRV (α2) (Morales et al., 2019). Although limited, findings suggest there may be a positive relationship between vmHRV and confidence.

***Exercise Psychology***

*Psychological Stress*

Multiple studies support the notion that exercise positively influences vmHRV, potentially acting as a buffer against the effects of psychological stress on the autonomic nervous system. This is often explored through an exercise intervention, fitness testing or self-reported physical activity. Aerobic exercise interventions improved vmHRV (RMSSD) during stressful periods (von Haaren et al., 2016), while a decrease in HRV (LF/HF) (von Haaren et al., 2016) and HRV (RLX Polar index reactivity) (Klaperski et al., 2014) was observed. Yoga interventions have also been found to influence HRV, with HRV (LF/HF) increasing in the yoga group, although no change was found pre/post in HRV (LFuns and HFuns) (Lin et al., 2015). When examining trained and untrained individuals, Zaffalon, Viana, Melo and Angelis (2018) found that active women had higher vmHRV (RMSSD, $HFms^2$), HRV (HFnu), and lower HRV (LF, LF/HF) after a mental stressor than sedentary women. However, the opposite relationship was found where trained individuals have a greater decrease in vmHRV when faced with a mental challenge: RSA (de Geus et al., 1990), $HFms^2$ (Franks & Boutcher, 2003), $HFms^2$ (Boutcher et al., 1998), $HFms^2$ (Sloan et al., 2011). Although participants with higher levels of stress from the past week had lower HRV (HFnu), this was independent of fitness levels (Dishman et al., 2000). Stress may also affect the body's reaction to exercise as shown in De Souza and colleagues (2020) work, where an increase in stress (higher work control, perceived stress, stress symptoms) resulted in lower vmHRV (RMSSD, SD1) withdrawal during a submaximal exercise test. Like sport, there are mixed findings in relation to exercise, stress, HRV and vmHRV.

*Emotion, Mood, and Affect*

Exercise can influence our moods and emotions, and HRV is often measured alongside to help better understand the physiological reactions associated with these psychological states. Interventions aimed at reducing anxiety (i.e., yoga) were found to decrease vmHRV (pNN50) and increase LF/HF when compared to control (Cheema et al., 2013). Albracht-Schulte and Robert-McComb (2018) found that yoga reduced anxiety, and after emotional stimuli were presented to participants, vmHRV (RMSSD) and HRV (LFnu) increased. However, other interventions have reduced self-reported anxiety but did not have an influence on HRV/ vmHRV parameters, in Qigong, HRV (LFnu, Hfnu) (Lin et al., 2018) or in Tai chi, vmHRV ($HFms^2$) and HRV ($VLFms^2$, $LFms^2$, $TPms^2$, LF/HF, LFnu, HFnu) (Zheng et al., 2018). To sum up, findings regarding anxiety and HRV were mixed across the included studies.

Researchers have investigated affective states, mood, and emotion regulation in exercise contexts in line with HRV. Increases in vmHRV (RMSSD) after exercise were positively associated with tension and tiredness (Meier & Welch, 2016). However, there was no relationship between affective states and vmHRV (RMSSD) when participants observed exercise images (Schinkoeth et al., 2019). In walking interventions, studies found no influence on HRV (SDNN, HFuns LFuns) (Gidlow et al., 2016), HRV (HFms) (Sakuragi & Sugiyama, 2006), but in one case mood was improved (Gidlow et al., 2016). In another study investigating mood and exercise withdrawal (Weinstein et al., 2007), baseline HRV (LF/HF) was a predictor of negative mood as a result of exercise withdrawal, although no changes in vmHRV (HFms$^2$) or HRV (LFms$^2$, HFms$^2$, LF/HF) were noted pre/post exercise withdrawal. Mood and recovery were positively influenced when vmHRV (RMSSD) was used as a guiding parameter to adjust a running programme when compared to controls doing a pre-defined fitness program (da Silva, 2020). When assessing emotion regulation to emotionally arousing stimuli, yoga practitioners displayed lower HRV (LF/HF) than recreational athletes (Wadden et al., 2018). To sum up, the link between emotion, mood, affect, and HRV is still unclear in the context of exercise, given few studies focused on vmHRV.

*Cognitive performance*

Exercise effects on cognitive performance together with HRV measurement was investigated in three main areas: longitudinal exercise interventions, acute exercise, and physical fitness. Long-term exercise interventions were found to increase vmHRV (RMSSD, HFms$^2$) over time (Albinet et al., 2016; Albinet et al., 2010). This increase in vmHRV was found to be related to cognitive improvement following a 12-week aerobic exercise program (Albinet et al., 2010) and 21-week swimming/aqua aerobics intervention (Albinet et al., 2016). However, a 12-week skiing intervention did not find any relationship between cognitive performance and HRV (HFnu) (Finkenzeller et al., 2011).

Short bouts of aerobic exercise (30 minutes) prior to cognitive performance have been found to increase HRV (LFnu) and subsequently cognitive performance in a trail making and reaction time test (Murray & Russoniello, 2012). Ludyga et al., (2019) found that only intermittent moderate intensity exercise helped to decrease reaction time in a Flanker task, however there were no associations between HRV (LF/HF) and cognitive performance. A study assessing levels of cognitive engagement in physical activity found a larger reduction in vmHRV (RMSSD) during physically active tasks in comparison to control (Benzing et al., 2016). Slow-paced breathing following acute exercise (burpees) improved inhibition performance but vmHRV (RMSSD) did not mediate performance improvement (Laborde et al., 2019).

Physical fitness has also been assessed alongside HRV and cognitive performance. Those who have higher levels of fitness tend to have higher vmHRV: $HFms^2$ (Alderman & Olson, 2014), RMSSD (Luque-Casado et al., 2016), and RMSSD (Franks & Boutcher, 2003; Luque-Casado et al., 2013). Although highly fit individuals tend to display higher vmHRV, this does not always mean that cognitive performance will be improved, as illustrated with $HFms^2$ (Alderman & Olson, 2014) and RMSSD (Luque-Casado et al., 2013). This was also demonstrated in older adults where vmHRV (RMSSD, SD1) was positively correlated with cognitive performance (e.g., card sorting task), however it was not shown that HRV mediated the relationship between cognition and physical fitness (de Oliveria Matos et al., 2020). This topic area shows some promise in enhancing cognitive performance via the exercise-vmHRV relationship, however results are inconsistent.

*Personality traits*

Personality traits are used in exercise psychology to assess a range of factors related to health behaviours. For example, high levels of trait self-control, which is linked to more positive health behaviours, was associated with higher levels of HRV (SDNN) (Daly et al., 2014), although more research is needed to draw conclusions.

*Self-efficacy*

Self-efficacy plays an important role in exercise psychology. Self-efficacy (defined as the beliefs in the ability to exercise over a period of time) and HRV was examined pre, during (steady state) and post-exercise. Only at post-exercise was self-efficacy found to be negatively related to HRV (HFnu) (Matsuo et al., 2015), although more research is needed to draw conclusions.

*Motivation*

Exploring motivational states in experimental research was found to influence HRV responses, for example motivational dominance (telic) was associated to increased vmHRV (RMSSD, $HFms^2$) prior to exercise (Kuroda et al., 2015). Temporary shifts in HRV (decreased LF/HF) were found to occur in high intensity exercise programs, and these shifts were associated to reduced state motivation to exercise (Crawford et al., 2020). Although limited, there is a potential relationship between motivational state and HRV.

*Subjective fatigue*

Subjective fatigue has been investigated in line with HRV in exercise contexts. During a cycling task with pleasant manipulated audio-visual stimuli (i.e., easy peddling and normal breathing), HRV (HFuns) increased and subjective fatigue was reduced (Barreto-Silva et al., 2018). In another study examining HRV monitored exercise (i.e., high intensity exercise programs), temporary shifts in HRV (decreased LF/HF) were found to occur, and these shifts were associated to increased global physical fatigue (Crawford et al., 2020). Results suggest that increased subjective fatigue may reduce HRV.

*Perceived wellness and life quality*

Perceived wellness and quality of life is also of interest within the exercise domain and HRV, given the links between wellbeing, health, and HRV (Thayer et al., 2009). Oliver, Morton, Baldwin and Datta (2020) examined perceived wellness, HRV and key physical markers of fitness, however they found no relationship between perceived wellness and HRV (VLF%, LF%, HF%, LF/HF, SDNN). When assessing quality of life across both physical activity and mindfulness in an aging population across a 10-year period, mindfulness meditation was found to improve HRV (HFnu) (Tang et al., 2020). Limited findings exist between the relationship of perceived wellness, quality of life and HRV.

**Discussion**

This paper aimed to systematically review the use of HRV within SEP. Following the systematic review of 118 papers of SEP research, it became clear that the application and interpretation of HRV was extremely varied. The following topics areas were found in sport psychology: psychological stress, precompetitive anxiety, cognitive function, HRV-Biofeedback, recovery, overtraining and injury, challenge and threat, pain, personality traits, motivation, mood, flow, self-efficacy, and self-confidence. Topic areas in exercise psychology included: psychological stress, emotion, mood and affect, cognitive performance, personality traits, self-efficacy, motivation, subjective fatigue, perceived wellness, and life quality.

*How is HRV being used in SEP?*

Some of the most common topics utilizing HRV across both SEP was to index psychological stress or anxiety. Within the sport psychology domain HRV, stress and anxiety were often linked to competitive responses (Cervantes Blásquez, 2009; D'Ascenzi et al., 2014; Iellamo, 2003; Morales et al., 2013; Morales et al., 2019; Sartor et al., 2017) , while exercise psychology mainly focused on the effects of exercise intervention and fitness level on stress and HRV (Boutcher et al., 1998; Franks & Boutcher, 2003; Klaperski et al., 2014; Liu et al., 2015; von Haaren et al., 2016; Zaffalon Junior et al., 2018). Cognitive performance was also explored in both domains with exercise psychology focussing on HRV's influence on cognitive performance in long-term interventions (Albinet et al., 2016; Albinet et al., 2010; Finkenzeller et al., 2011), short -term interventions (Benzing et al., 2016; Laborde et al., 2019; Ludyga et al., 2019; Murray & Russoniello, 2012) and fitness levels (Alderman & Olson, 2014; Franks & Boutcher, 2003; Luque-Casado et al., 2016; Luque-Casado et al., 2013). In sport the application of the relationship between HRV and cognitive performance was mixed (e.g., the influence of fatigue) and findings were varied (Dupuy et al., 2018; Dupuy et al., 2014; Gantois et al., 2020; Landolt et al., 2017; Sartor et al., 2017).

Within sport psychology, some topics relating to HRV already received extensive attention, such as HRV-biofeedback (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021) and recovery/overtraining (e.g., Dobson et al., 2020; Hauer et al., 2020; Nicolas et al., 2019; Tibana et al., 2019). However, there were also some less researched applications of HRV, such as pain (Matylda et al., 2020; Thornton et al., 2019) and motivation (Korobeynikov, 2011). This was also present within exercise psychology such as motivation (Crawford et al., 2020; Kuroda et al., 2015) and self-efficacy (Matsuo et al., 2015). While there were some interesting findings within these topics, the links between HRV theory and the application of HRV measurements were more tenuous.

*What can HRV tell us about SEP?*

Despite data from 118 papers included within this review, we do not have many clear findings on what HRV can tell us about SEP phenomena. The key issue here being that many of the results are mixed and contradictory, which is mainly linked to methodological weaknesses or limited theoretical underpinning of the studies. In an effort to summarise some of the meaningful outcomes, we now discuss findings related to vmHRV only, and suggest potential mechanisms that exist in relation to behavioural, psychological and social phenomena.

vmHRV plays a major role in adaptation to our environment (Thayer et al., 2009), which is important for researchers in SEP. One observation that can be taken from the findings is that when athletes experience anxiety prior to actual competition (as opposed to training or simulated competition) a reduction in vmHRV can occur (Ayuso-Moreno et al., 2020; Morales et al., 2013; Mateo et al., 2012; Cervantes Blásquez, 2009). This reduction in vmHRV could suggest that athletes who experience higher levels of anxiety are subsequently then less able to effectively regulate themselves in demanding environments, such as competition. In this scenario it could be suggested that an athlete's resources are being "used up" and behaviours are driven towards fight or flight responses due to the perceived threat of competition (vagal withdrawal). This means that there are subsequently less resources available for mental effort requiring top-down prefrontal functioning to utilise anxiety reducing strategies, which require higher levels of vmHRV. This is why strategies such as HRV-biofeedback or slow-paced breathing are often used as an intervention for athletes experiencing anxiety, in an effort to improve psychophysiological functioning (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021). Although in the reported studies vmHRV was only measured prior to competition, so we do not yet know how athletes may respond to and recover from multiple experiences of anxiety within the sporting domain. It should also be noted that the importance of the situation, level of competition, and sport demands may also influence anxiety levels and subsequent vmHRV.

In a similar vein, demands placed on the exerciser or athlete are also associated with a decrease in vmHRV, for example in cases of psychological stress (e.g., Móra et al., 2022; De Souza et al., 2020; Frenkel et al., 2019) and overtraining (e.g., Hynynen et al., 2008), and pain (e.g., Britton et al., 2019). Again, this suggests that vmHRV is associated to the use of resources to facilitate adaptation to demand (Thayer et al., 2009), however without understanding the recovery from the demand, it is difficult to ascertain whether this decrease is functional for psychological response and behaviour. In essence a decrease in vmHRV could suggest a "negative response" as described above in relation to anxiety, or a decrease in vmHRV could be seen as a facilitative response to cope with demands if the athlete/exerciser is able to return to resting baseline levels. Therefore, understanding the role of vmHRV in recovery from demands is also crucial to further understand HRV's role in SEP more clearly.

From the findings it could be suggested that vmHRV does have a positive role in the recovery from demands. Subjective indicators of recovery were found to be positively related to vmHRV (Vacher et al., 2018; Flatt et al., 2017; Parrado et al., 2010), suggesting that athletes subjective psychological state is aligned with vagal recovery, which would be a useful monitoring tool for practitioners wanting to understand holistic recovery during times of demands (e.g., competition, training phases, non-sporting stressors such as exam periods). Although mixed findings were presented, this area of research has promise given HRV's use in monitoring training load in athletes (Bellinger et al., 2016). Given vmHRV seems to be linked with subjective recovery, this should prompt researchers to include measures of HRV "post - event" to help evaluating the recovery status of athletes (Laborde et al., 2018).

Enhancing vmHRV is often a key aim of studies in SEP, given higher levels of vmHRV are linked to enhanced prefrontal functioning and cognitive performance (Thayer et al., 2009; Laborde et al., 2018). Within exercise psychology, exercise interventions are often aimed at increasing vmHRV and subsequently improve cognitive performance in ageing populations (Albinet et al., 2016; Albinet et al., 2010). In sport psychology using HRV biofeedback to increase vmHRV has also been shown to support effective sporting performance and reduce anxiety (Paul and Garg, 2012). While the evidence for enhancing vmHRV with specific aims in SEP is still quite limited, enhancing vmHRV via various strategies appears to be impactful (Jimenez Morgan & Molina Mora, 2017; Laborde et al., 2022; Laborde, Mosley & Ueberholz, 2018; Pagaduan et al., 2020; Pagaduan et al., 2021; Schmaußer et al., 2022; Sevoz-Couche & Laborde, 2022; Vanderhasselt & Ottaviani, 2022).

Although HRV has such promise within SEP, some of the findings have little significance due to methodological limitations such as measurement, parameters used and interpretation. It also became clear that theoretical developments have been mostly overlooked in studies within SEP, and as a result, many of the studies discussed within this review have limitations, particularly around the conclusions drawn from the data gathered. Given the heterogeny of results, an important aspect of this scoping review was to highlight the common pitfalls observed within SEP research using HRV.

*Common pitfalls in SEP research using HRV*

(1) Theoretical underpinning of HRV

It is crucial that research is driven by theory to ensure robust hypothesis testing and to provide insightful conclusions within the field of SEP. This is a larger issue within the psychological sciences whereby a lack of overarching theoretical frameworks creates hypotheses across diverse domains and research ideas from personal intuitions (Muthukrishna, 2019). It is unsurprising therefore that researchers in the field are calling for more theoretically driven work and developing overarching theoretical frameworks (Muthukrishna, 2019). Theory should be at the forefront of HRV use in SEP, to ensure a meaningful interpretation, comparability of results, and to enable a better understanding of the psychophysiological mechanisms in relation to HRV. We appreciate that in some areas such as training science, the theoretical underpinning of vmHRV for subjective recovery is scarce and therefore should be developed in the future.

There are some robust examples of empirical work that is based on HRV theory. Some examples include the work of Albinet and colleagues (2016) and Luft, Takase and Darby (2009) who based their hypothesis and methodological design on theoretical frameworks of HRV, specifically the neurovisceral integration model (Thayer et al., 2009). More recently, researchers also used the vagal tank theory to structure experimental procedures with HRV (e.g., You et al., 2021a). However, it is pertinent to note that most studies could be classified as a-theoretical, given they did not rely on one of the main theories related to HRV (see Laborde et al., 2017; Shaffer et al., 2014). Many papers infer the meaning of HRV and do not use theoretical frameworks to interpret their data, such as researchers who suggest HRV is a measure of stress.

Investigating stress with HRV is certainly one of the biggest theoretical pitfalls in SEP research. While studies examining stress are important in SEP, it is imperative to highlight why we cannot fully measure stress with HRV. Although there is evidence around the appraisal process regarding the integration of HRV within stress and health (Thayer et al., 2012), research in SEP often uses HRV as the sole marker of the stress response. The full physiological response to stress is complex (Baumann & Turpin, 2010; Carrasco & Van de Kar, 2003; Charmandari et al., 2005; de Kloet et al., 2005; Seaward, 2006). Two major neuroendocrine systems assist the organism adaptation to stress situations: the HPA (Hypothalamic-Pituitary-Adrenal)-axis, with cortisol as a main biomarker (Kirschbaum et al., 1999), and the autonomic nervous system (Charmandari et al., 2005). The autonomic nervous system is then divided into two branches, the sympathetic nervous system - indexed for example via pre-ejection period (Sherwood et al., 1990); and the parasympathetic nervous system, indexed with vmHRV (Berntson et al., 1997; Laborde et al., 2017). Importantly, it has now repeatedly been shown that HRV (LF) cannot provide a reliable indicator of (cardiac) sympathetic nervous activity (Ackermann et al., 2021; Goldstein et al., 2011; Martelli et al., 2014; Moak et al., 2007; Pomeranz et al., 1985; Rahman et al., 2011; Reyes del Paso et al., 2013). Consequently, the so-called "sympatho-vagal balance" which is based on the LF/HF ratio, is an inaccurate conceptualization (Billman, 2013; Heathers, 2012). These measures have been used in many of the studies discussed above, with limited studies also considering the Hypothalamic-Pituitary-Adrenal (HPA)-axis (e.g., cortisol - Iellamo, 2003), or a measurement of sympathetic nervous activity, with for example pre-ejection period (Franks & Boutcher, 2003) or skin conductance (Finkenzeller et al., 2011), to obtain a more holistic physiological understanding of stress.

In a similar vein, often studies would use HRV to determine successful cognitive performance. For example, following Thayer's neurovisceral integration model (2009), as it assumes higher levels of vmHRV would increase executive performance, studies have used exercise to increase vmHRV to subsequently improve cognitive performance (Albinet et al., 2016; Albinet et al., 2010; Laborde et al., 2019). On the contrary, in a-theoretical research some authors consider HRV as an arousal measure and suggest that specific types of executive performance (for example inhibition) are actually enhanced as a result of sympathetic dominance, often indicated by the LF/HF ratio (Ludyga et al., 2019) or LFnu (Murray & Russoniello, 2012), which is not supported by theory (Thayer et al., 2009). In some cases, the type of cognitive performance investigated is not classified as executive functioning, for example studies using a battery of tests in which some of these are not related to executive function, e.g., a reaction time test (e.g., Murray & Russoniello, 2012) or peripheral perception (Finkenzeller et al., 2011). This would not be in line with theory, given the neurovisceral integration model (Thayer & Lane, 2009) assumes a relationship only between executive cognitive performance and vmHRV. Furthermore, in some studies the HRV parameter assessed was not compared with cognitive performance, but with a subjective measure of cognitive load (Sangachin et al., 2016) or cognitive engagement (Benzing et al., 2016). It is crucial to note that only cognitive performance relying on executive functioning is theoretically suggested to be associated to vmHRV, based on the neurovisceral integration model (Penna et al., 2018; Smith et al., 2017; Thayer et al., 2009), and researchers aiming to investigate cognition and HRV in SEP should first clearly reflect about the theoretical implications of their research.

(2) HRV measurement

From our review, we found that 54 studies used multi-lead ECG devices to measure HRV. It is recommended to use multi-lead ECG devices to measure HRV whenever possible (Berntson & Stowell, 1998; Laborde et al., 2017), a more detailed discussion of HRV measures being presented in Supplementary Material 2b. Despite the growing accessibility of portable ECG devices (for example eMotion Faros, Bittium), within the applied domain, technology based on watches or smartphone apps - for example Elite HRV, HRV4Training, iThlete (Stone et al., 2021) - allow for “in the moment” feedback, and are largely accessible – so we do not discourage their use here for research in the applied field, given in some conditions the HRV parameters they provide are highly correlated to those obtained with multi-lead ECG (Stone et al., 2021). However, we must stress that if researchers decide to use these devices, they should still clearly state this in the limitations of their research, as only a multi-lead ECG signal would enable to clearly identify heart beats (Berntson & Stowell, 1998; Laborde et al., 2017).

One thing that became apparent when completing the critical appraisal checklist (Hong et al., 2018) was that many studies did not control for confounding variables that can influence HRV measurements. For example, age (Umetani et al., 1998) and gender (Koenig et al., 2014) are key confounding variables for interpreting HRV data, and many studies did not account for this in their analyses. Researchers should check these key variables before making assumptions from the data (a checklist of potential confounding variables is provided as a Supplementary Material in Laborde et al., 2017). One consideration, particularly in the field of SEP, is around the role of movement on HRV, as limited movement should occur when assessing HRV in a psychological context (Laborde et al., 2017). Movement influences the autonomic nervous system (Brodal, 2016), and therefore psychological interpretation with vmHRV is compromised when the participant is moving. It is currently not possible to dissociate the influence of movement on vmHRV from other psychological mechanisms linked to self-regulation, even if some attempts exist outside the sport and exercise context (Brown et al., 2020). To address this issue, some studies measured HRV when the participant was not moving, for example during competitive breaks (Bisschoff, 2016) or after physical exertion (Penna et al., 2018). Other methods include deleting the sections of data where excess of movement occurs (e.g., Hansen et al., 2003; Johnsen et al., 2003) and using algorithms such as continuous wavelet transformation to minimize motion artifacts (Villarejo et al., 2013). These methods however still require further research prior to drawing conclusions associated to psychological phenomena.

(3) Interpretation of HRV results

Finally, we want to highlight some challenges with the interpretation of HRV results within SEP. One of the most reported parameters within this review was LF/HF, with 49.1% of papers reporting it (*n* = 58). The LF/HF ratio is often mistakenly referred to as the "sympathovagal balance" (Billman, 2013; Heathers, 2012) which is a conceptualization based on the assumption that LF represents sympathetic nervous activity. Extensive research, including blockade studies, have now repeatedly shown that LF is a mix of sympathetic, parasympathetic, and baroreflex activity (Ackermann et al., 2021; Goldstein et al., 2011; Martelli et al., 2014; Moak et al., 2007; Pomeranz et al., 1985; Rahman et al., 2011; Reyes del Paso et al., 2013). We strongly urge researchers and practitioners to avoid using the LF/HF ratio, and to be particularly critical when assessing research findings based on it.

To provide a guide for authors and to enable further understanding of HRV parameters, we have created a table to highlight the HRV parameters and their physiological origin to help interpreting findings within SEP (see Table 2c). We also recommend that the focus of research should be vmHRV, given its links with theory as outlined above, but authors should also present the other main HRV parameters (e.g., LF, SDNN), for example in an additional table in the manuscript or as Supplementary Material. This will allow the interested reader a full overview of all HRV parameters, avoiding cherry-picking, and improving generalizability and comparability of results across studies.

INSERT TABLE 6 AROUND HERE

**Limitations and Future Directions**

Whilst this review was conducted with transparency with the full protocol available on the OSF and in line with current guidance regarding systematic reviews (PRISMA, SWiM), it is important that limitations are acknowledged. Firstly, this review was limited to the SEP domain. Due to this some studies within performance domain were excluded, for example chess (Fuentes-Garcia et al., 2019; Troubat et al., 2009), dance (Edmonds et al., 2018) and emerging domains like esports (Pedraza-Ramirez et al., 2020). Given they did not explicitly fit our criteria of sport or exercise ([b] examined HRV in conjunction with psychology in sport, exercise or physical activity domains), or elements of the definition of sport that we used. We were specifically focusing on SEP studies, rather than the broader performance domain. Considering this limitation, we encourage researchers to review the use of HRV in other performance domains to compliment the current findings of this review. A limitation of the search terms is that the authors used theoretical frameworks to guide their decisions and therefore only included "parasympathetic activity" and not "sympathetic activity". In addition, they did not include broader HRV terminology such as "cardiac activity" or "autonomic activity". On reflection, this may have restricted the search, and subsequently this could be a contributor to more papers being identified through forward and backward searching. Another limitation in the current review is that it mainly reflects published work within a research domain, rather than what happens in professional practice scenarios (e.g., Gross et al., 2017). Therefore, this review may not fully reflect how practitioners use HRV in day-to-day consulting with clients, which would be a useful investigation in the future.

We prompt authors to use theory and methodological guides within their future work to ensure rigorous testing of HRV. We have highlighted the importance of using HRV-based theory to effectively plan and implement robust research questions (Muthukrishna, 2019) and we encourage researchers and practitioners in SEP to consult the relevant theories (Gidlow et al., 2016; Laborde et al., 2018; Lehrer, 2013; Porges, 1995; Smith et al., 2017; Thayer et al., 2009). Similarly, researchers should use methodological guidelines for HRV (Catai et al., 2020; Laborde et al., 2017; Quintana et al., 2016; Quintana & Heathers, 2014), to produce meaningful HRV research in the SEP domain. Given the broad aim of this scoping review, it is recommended that if authors are specifically interested in the relationships between individual psychological constructs and HRV, concise systematic reviews should be conducted. Based on this, we have created an overview table (Table 6) to act as a benchmark when using HRV in SEP to guide researchers in their future work.



## Conclusion

The aim of this paper was to understand how HRV is being used within SEP. There were many applications of HRV to SEP, however those focussing on vmHRV and its role in adaptation (e.g., responses to competition, recovery and cognitive performance) provided the most meaningful results. We found three critical areas of consideration for SEP: 1. theoretical underpinning of HRV, 2. HRV measurement, and 3. interpretation of HRV results. We hope the current paper will highlight previous issues and guide SEP researchers and practitioners in their future work. Overall, there is huge potential for HRV, in particular vmHRV, to be effectively measured within SEP to yield a better understanding of the phenomena of interest and management of HRV use in the future.

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Table 1: Overview of HRV theories relevant to SEP application (for a more detailed overview about theories related to HRV, see Laborde et al., 2017; Shaffer et al., 2014)

| HRV theory | Overview | Applications to SEP |
|---|---|---|
| Polyvagal theory (Porges, 1995) | This theory suggests that vagal activity is an in-built system to drive and support behavioural adaptations to the social environment, and facilitate emotional responding (Porges, 1995). This theory uses the analogy of the vagal brake, suggesting that when the brake is applied, it causes an increase in vagal activity, fostering facilitative behavioural responses such as a calm approach to a pressure situation. When the brake is released, sympathetic activation is then dominant to help foster behaviours that are more adaptive to threatening situations. | • Self-regulation<br>• Stress<br>• Behavioral responses |
| Neurovisceral integration model (Thayer et al., 2009) | This model introduced the notion that cardiac vagal activity is an output of the central autonomic network (Thayer & Lane, 2009). The central autonomic network involves specific brain areas (for an overview see Thayer and al., 2009, Figure 1, p.144), such as the prefrontal cortex, an area of the brain that helps to adapt to environmental challenges and changes, which controls and coordinates functions linked to inhibitory, attentional and memory processes (Thayer et al., 2009). | • Self-regulation<br>• Wellbeing<br>• Health<br>• Cognitive performance (executive function) |
| Psychophysiological coherence model (McCraty & Childre, 2010) | An overarching model encompassing psychophysiological systems, the functioning of which determine the range of one's ability for self-regulation and to adapt to environmental challenge. The model states that positive emotions shift the system as a whole into a more globally coherent and harmonious physiological mode, associated with improved system performance, ability to self-regulate, and overall wellbeing (McCraty & Zayas, 2014). | • Self-regulation<br>• Emotion |
| Resonance frequency breathing model (Lehrer, 2013) | Resonance occurs when participants voluntarily produce maximal heart rate oscillations via breathing to trigger cardiovascular resonance (Lehrer, 2013). Based on the phase coupling between respiration at a specific pace, blood pressure and heart rate, which can be used to trigger the resonance properties of the cardiovascular system given its action on the baroreflex. This phase coupling is suggested to improve gas exchange and oxygen saturation, as well as an increase of vagal afferences (Lehrer, 2013; Lehrer & Gevirtz, 2014). Breathing at a particular rate (between 4.5 to 6.5 breaths per minute), the so-called resonance frequency, is then suggested to increase cardiac vagal activity (Shaffer & Meehan, 2020). | • HRV-Biofeedback<br>• Slow-paced breathing |

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| Vagal tank theory (Laborde et al., 2018) | This theory builds on both the polyvagal theory (Porges, 1995) and on the neurovisceral integration model (Thayer et al., 2009), but considers further adaptation responses involving tonic (i.e., value at a specific time point) and phasic (i.e., a value reflecting a change between two time points) measurements of cardiac vagal activity, focusing on three measurements aspects coined the three R's (Resting, Reactivity, Recovery). Previous research has mainly focussed on resting cardiac vagal activity only, whilst reactivity and recovery measures were rather neglected. The premise of this theory is that both tonic and phasic HRV should be considered with the 3 R's in order to gain a full understanding of the way the organism adapts to internal and external stimuli (Laborde et al., 2018). It also suggests that different patterns may exist when facing a demanding or replenishing stimulus – such as a stressor task or using slow-paced breathing. | • Self-regulation<br>• Methodological guidance |

Table 2: Methodological considerations using HRV

2a: Defining HRV measurement times (according to Laborde et al., 2018; Laborde et al., 2017)

| **Measurement time** | **Meaning** | **Measurement type** |
|---|---|---|
| Resting (Baseline) | First resting measure. This is taken prior to any experimental manipulation or a specific event. | Tonic |
| Event | Measure taken during an event, e.g. during a cognitive task, or during a mental / physical stressor | Tonic |
| Resting (post-event) | Measure taken post-event, e.g. post-task, between manipulations, or post-intervention. | Tonic |
| Reactivity | Difference between resting (baseline) and event | Phasic |
| Recovery | Difference between event and resting (post-event) | Phasic |

2b: Heart rate variability measurement devices

| Measurement device | Device examples | Description | Validity/Reliability |
|---|---|---|---|
| Electrocardiogram (ECG) (multi-lead) | eMotion Faros 180 (Bittium); Amlab Physiograph, Model 1.7; Biopac MP35 | Detects electrical activity in the heart via multi lead electrodes (Stone et al., 2021) | Gold standard for HRV measurement is to collect multi-lead ECG data, as it allows researchers to visualize the ECG signal, enabling to precisely detect heartbeats, and potentially identify missed or extra ones, or to detect specific cardiac events such as extra-systoles, ensuring precise artifact correction (Berntson & Stowell, 1998; Laborde et al., 2017). |
| Electrocardiogram (ECG) (chest belt) | Polar® heart rate monitor; Suunto® t6 heart rate monitor | Detects electrical activity in the heart via a chest belt (Stone et al., 2021), often connected to watches or smart phone apps which are commonly used in sport and exercise. | Can cause more artifacts in the data due to movement, although there is some evidence to suggest that chest belts could provide reliable and valid results to measure HRV parameters (Flatt et al., 2017; Stone et al., 2021; Wallen et al., 2012; Weippert et al., 2010). |
| Photoplethysmography (PPG) | emWave®; ithlete™ | Uses optical techniques (light waves) to infer heart rate from the quantification of volume changes in distal blood flow (Georgiou et al., 2018). Often PPG is used in devices such as watches, smartphone cameras, finger sensors, or earlobe clips. | There are fluctuations in accuracy (Stone et al., 2021), PPG being for example less valid in non-resting conditions (Schafer & Vagedes, 2013). There is some evidence to suggest that devices using the PPG technology (smart watches, smartphone cameras and finger sensors) provide the most reliable and valid results to measure HRV parameters in resting conditions (Flatt et al., 2017; Stone et al., 2021; Wallen et al., 2012; Weippert et al., 2010). |

2c: HRV parameters (adapted from Berntson et al., 1997; Laborde et al., 2017; Malik, 1996; Shaffer & Ginsberg, 2017)

| | Parameter | Description | Unit | Physiological origin | vmHRV |
|---|---|---|---|---|---|
| Time-domain | SDNN (SDRR, STDRR, SDIBI) | Standard deviation of all R-R intervals | | Cyclic components responsible for heart rate variability | x |
| | RMSSD | Root mean square of successive differences | ms | Cardiac vagal activity | ✓ |
| | RMSSD index | Presented as a number between 1-100 from the ithlete™ device | | To some extent related to cardiac vagal activity | x |
| | pNN50 | Percentage of successive normal sinus RR intervals more than 50ms | ms | Cardiac vagal activity | ✓ |
| | RSA | Respiratory sinus arrhythmia, which reflects the variations accompanying respiration (several methods to derive RSA: peak-to-trough, Porges-Bohrer, difference between maximum and minimum cardiac interbeat interval per beat) | Depending on the method used | Suggested to reflect cardiac vagal activity, but is not completely independent from sympathetic activity (Farmer et al., 2016; Taylor et al., 2001) | ✓ |
| Frequency-domain | TP | Total power of frequency domain in 24 hours (excluding ULF for short term recording) | $ms^2$ | Total power of HRV | x |
| | | | % | | x |
| | | | nu | | x |
| | ULF | Ultra-low frequencies | $ms^2$ | Circadian oscillations, core body temperature, metabolism and the renin-angiotensin system | x |
| | VLF | Very-low frequencies | $ms^2$ | Long-term regulation mechanisms, thermoregulation and hormonal mechanisms | x |
| | LF | Absolute power of low frequencies | $ms^2$ | Mix of cardiac sympathetic and vagal activity, as well as baroreflex activity. *$LFms^2$ – can reflect cardiac vagal | ✓* |
| | | Percentage power of low frequencies | % | | x |
| | | Normalised units of low frequencies | nu | | x |

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| | | | | activity during slow-paced breathing (6cpm) (Kromenacker et al., 2018) | |
| | HF | Absolute power of high frequencies | $ms^2$ | Cardiac vagal activity for $ms^2$ only | ✓ |
| | | Percentage power of high frequencies | % | For % and normalized units, their calculation entails other parameters such a LF, which means that a clear physiological origin can't be determined for them | x |
| | | Normalised units of high frequencies | nu | | x |
| | LF/HF | Low frequencies / high-frequencies ratio | $ms^2$ | Unclear, suggested mix of cardiac sympathetic and vagal activity | x |
| | | | % | | x |
| | | | nu | | x |
| **Non-linear indices** | SD1 | Standard deviation - Poincaré plot Crosswise | ms | Unclear, depicts quick and high frequent changes in heart rate variability. It is an identical metric as RMSSD, and thus is suggested to index cardiac vagal activity (Ciccone et al., 2017) | ✓ |
| | SD2 | Standard deviation - Poincaré plot Lengthwise | ms | Unclear, depicts long-term changes in heart rate variability | x |
| | SD1/SD2 | Ratio of SD1/SD2 | ms | Unclear, suggested mix of cardiac sympathetic and vagal activity | x |
| | SampEn | Sample entropy, which measures the regularity and complexity of a time series | | Measure of signal regularity and complexity | x |
| | α1 | Detrended fluctuation analysis, which describes short-term fluctuations | | Reflects the baroreceptor reflex | x |
| | α2 | Detrended fluctuation analysis, which describes long-term fluctuations | | Reflects the regulatory mechanisms that limit fluctuation of the beat cycle | x |

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| **Others** | RLX | Derived from Polar which is an approximation of SD1 | ms | Mix of sympathetic and parasympathetic modulation of heart rate | x |
| | Coherence | Percentage of time spent in each frequency domain | hz | No coherence = sympathetic (0.04hz), almost coherent (0.1hz). cardiac coherence = parasympathetic (0.5hz) | x |

Note: unit abbreviations; ms = milliseconds, $ms^2$ = millisecond squared; nu = normalized unit, hz = hertz

Table 3: Sport Psychology Papers

| Study | Participants | Protocol | HRV theory reported | HRV device and measurement | HRV Parameters Reported | Main Findings |
|---|---|---|---|---|---|---|
| Ayuso-Moreno, Fuentes-García, Collado-Mateo, and Villafaina (2020) | Fourteen female soccer players ($M_{age}$ = 23.78 ± 4.93) | Across two microcycles (including one high demand and one low demand match), baseline HRV, pre-competition HRV and anxiety (CSAI-2R) were measured. | Model of autonomic nervous system functioning in psychopathology[1] | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline and pre-match) | **vmHRV**<br>pNN50, RMSSD, HFms², SD1<br><br>**HRV**<br>LF ms², LF/HF, TP, SD2 | Differences in resting HRV vs pre-competitive HRV were only observed in high-demand matches, decreases in vmHRV (pNN50, RMSSD, HFms², SD1) and in HRV (Total Power, and SD2) / increases in the SNS index, stress index, mean HR, LF, LF/HF. |
| Bisschoff, Coetzee and Esco (2016) | Twenty-two male elite badminton athletes ($M_{age}$ = 23.3 ± 3.9) | Players were measured before, during and after 46 matches – measurements included mood (POMS) and HRV. | N/A | Polar Team² Pro<br><br>(R-R interval)<br><br>Resting (baseline), event (during match), resting (post-match) | **vmHRV**<br>Ln-SD1, LnRMSSD,<br><br>**HRV**<br>Peak VLF Hz, Peak LF Hz, Peak HF Hz, Ln-LFnu, Ln-HFnu, VLF%, LF%, HF%, Ln-LFnu/HF Ln-HFnu, Ln-SD2, LnSDNN<br><br>(Log transformed) | A positive correlation was found between a number of subjective recovery markers and vmHRV during the match (e.g. sleep quality and lnRMSSD). |
| Botonis, Smilios and Toubekis (2021) | Nine elite male water polo athletes ($M_{age}$ = 25.6 ± 4.7) | Athletes monitored both in preseason (5 weeks) and in season (4 weeks). Morning HRV was measured and 30 minutes post-training internal training load was measured (including rate of perceived exertion). | N/A | Polar V800<br><br>(R-R interval)<br><br>Resting (baseline) | **VmHRV**<br>LnRMSSD | A negative correlation was found between internal training load and $LnRMSSD_{mean}$ during the preseason, only trivial results were found during the season. |
| Britton, Kavanagh and Polman (2019) | Sixty-one undergraduate students (30 | Participants completed the Perceived Stress Reactivity Scale for | Neurovisceral integration model[2] | eMotion Faros 180° | **vmHRV**<br>HFms² | Lower vmHRV (HFms²) was related to greater ratings of stress, pain and |

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| | participating in competitive sport, 31 non-athletes) ($M_{age}$ = 20.11 ± 1.25, Male = 28) | Adolescent Athletes, followed by the socially evaluated cold pressor test. | | (ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event), reactivity, recovery | (Log transformed) | unpleasantness during the task. No other relationships found. |
| Ceccarelli, Giuliano, Glazebrook and Strachan (2019) | Ninety-one adult athletes ($M_{age}$ = 21.4 ± 3.47, 58% female) | Participants exposed to a laboratory stressor (recalled sport failure imagery), HRV and subjective psychological measures taken. | Neurovisceral integration model[3,4,5], Polyvagal theory[6], Vagal tank theory[7] | ProComp Infiniti photo-plethysmograph<br><br>(PPG derived R-R interval)<br><br>Resting (baseline), reactivity and recovery | **HRV**<br>HFuns<br><br>(Log transformed) | Self-compassion was related to an increase in HRV (HFuns) reactivity (from baseline to task) when exposed to the stress induction, which was linked to a dampened stress response. No relationships were found with recovery or fear of self-compassion. |
| Cervantes Blásquez, Font and Ortís (2009) | Ten masters swimming athletes ($M_{age}$ = 47 ± 6.81, 6 female) | 30 minutes prior to a simulated competition and a real competition, swimmers had anxiety (CSAI-2) and HRV taken for 10 minutes. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8] | Polar S810i heart rate recorder with a Polar T61 elastic electrode belt<br><br>(R-R interval)<br><br>Resting (supine baseline) | **vmHRV**<br>RMSSD, HF $ms^2$, pNN50, SD1<br><br>**vmHRV**<br>STDRR, SD2, VLF %, LF %, HF %, LF/HF %, VLF $ms^2$ , LF $ms^2$ , LF nu, HF nu (AR) | Precompetitive anxiety was higher in the real competition than the simulated competition. vmHRV (RMSSD, SD1, HF $ms^2$) and HRV (HFnu) were significantly decreased in the real competition when compared to the training competition. HRV (LF/HF) was significantly higher in the real competitive condition. |
| Choudhary, Trivedi and Choudhary (2016) | Twenty-four national level running athletes ($M_{age}$ 22.54 ± 1.72 years) | 10 week slow-paced breathing biofeedback intervention (experimental group) vs control. Stress (GSR) and performance measured pre- and post-intervention. | Resonance frequency model[9] | Procomp 5 Infiniti system<br><br>(ECG derived R-R)<br><br>Resting (baseline), event (biofeedback training), resting (baseline) | **HRV**<br>VLFuns, LFuns, HFuns, LF/HF | As a result of slow-paced breathing biofeedback training significant increases in HRV (LF/HF) and VO2, and significant decreases in skin conductance and running time were observed. |
| D'Ascenzi et al. (2014) | Twelve elite female volleyball athletes ($M_{age}$ 26.9 ± 4.5 years) | HRV measured in the lead up to competition (2 days before, 1 day before and morning of) | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8] | Heart rate monitor MC030, MINIcardio ProTM<br><br>(R-R interval) | **vmHRV**<br>RMSSD, lnHF $ms^2$ pNN50 %, SD1<br>**HRV**<br>STD (ms), SD2, SD1/SD2, lnVLF $ms^2$ , lnLF $ms^2$, | HRV (LF/HF% and LF/HF$ms^2$) was inversely correlated to technical performance (reception). Increase in HRV (VLF%) in starting players across the days leading up to the match. |

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| | | | | Resting (Supine morning recording) | (lnHF), LF %/HF%, LFn.u./HFn.u., lnLF/lnHF<br><br>(log transformed) | |
| Dobson, Harris, Calytor, Stroud, Berg and Chrysosferidis (2020) | Thirteen swimming athletes ($M_{age}$ 19 ± 1.0) | Measurements of HRV and psychological variables (RESTQ-52, Burnout) were taken at three points across a season: 1) beginning, 2) 50% training increase, 3) overload phase. | N/A | Finapres Finometer Pro<br><br>(R-R interval)<br><br>Resting (baseline), event (handgrip) | **vmHRV**<br>LnRMSSD | Over the season vmHRV (lnRMSSD) decreased. However, no significant correlations were found between the psychological variables and vmHRV (lnRMSSD). |
| Dupuy et al. (2014) | Eleven male endurance athletes ($M_{age}$ 29.5 ± 9.3) | Athletes were subjected to periods of overload and tapering to induce overreaching. HRV and executive and non-executive performance (Stroop) were assessed. | Neurovisceral integration model[3] | S810, Polar Electro Oy<br><br>(R-R interval)<br><br>Resting (baseline), event | **vmHRV**<br>RMSSD, HF $ms^2$<br><br>**HRV**<br>SDNN, HFnu, LF $ms^2$, LF/HF $ms^2$, LF/HF<br><br>(FFT) | Across baseline, overload and tapering periods, there were no effects on vmHRV (RMSSD, HF$ms^2$) and other HRV parameters (SDNN, HFnu), when examining these during executive and non-executive performance. VmHRV markers (RMSSD, HF$ms^2$) were not linked to cognitive performance. |
| Dupuy, Bosquet, Fraser, Labelle and Bhrer (2018) | Forty-two masters athletes (age range 49-70) | Athletes were split into two age groups (49-59, 60-70) and fitness groups (low fit, high fit), those in the high fit group were considered to be master athletes. Submaximal VO2, cognitive (neuropsychological and dual task tests) and HRV were measured across three separate laboratory visits. | Neurovisceral integration model[3,5], Polyvagal theory[10] | Polar S810, Polar Electo Oy<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, HF $ms^2$, SD1<br><br>**HRV**<br>LF $ms^2$, LF+HF, LF/HF, LFnu, HFnu, SD2 | Higher cardiovascular fitness was linked to better dual task performance which was mediated by cardiac autonomic control. Only a trend for vmHRV (RMSSD, SD1) and HRV (HFnu) parameters were shown to be positively linked to the executive elements of the cognitive tests. |
| Dziembowska et al. (2016) | Forty-one male basketball and football athletes ($M_{age}$ 18.34 ± 1.36, 11 basketball) | Slow-paced breathing biofeedback vs control group, measured HRV, EEG, anxiety and self-esteem. Slow-paced breathing biofeedback | Psychophysiological coherence model[11] | Photoplethysmographic (PPG) ear sensor, emWave PC Stress Relief System | **HRV**<br>TP$ms^2$, LF $ms^2$, HF $ms^2$, LF/HF (coherence index)<br><br>(FFT) | Athletes in the slow-paced breathing biofeedback group had a significant reduction in state anxiety (STAI) and vmHRV (HF $ms^2$) from pre to post intervention. The slow-paced breathing biofeedback group had an increase in HRV |

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| | | group received ten sessions over three weeks. | | (PPG derived R-R interval)<br><br>Resting (baseline pre/post intervention) | | ($LFms^2$) and Coherence index (LF/HF) from pre to post intervention. No changes occurred in the control group. |
| Flatt, Esco and Nakamura (2017) | Seventeen male sprint swimming athletes ($M_{age}$ 21.6 ± 1.8) | Athletes took daily measures of HRV and wellness measures (sleep, fatigue, muscle soreness, stress and mood) for a period of four weeks training. | N/A | ithlete™, HRVfit LTD<br><br>(PPG derived R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>LnRMSSD<br><br>(Natural log transform) | Higher levels of vmHRV (RMSSD) was directly linked to better sleep quality, fatigue, stress and mood. Lower levels of vmHRV (RMSSD) were linked to worse sleep quality, fatigue, stress and mood. No effects were found for muscle soreness. |
| Fortes et al. (2017) | Sixty-eight swimming athletes ($M_{age}$ 15.6 ± 0.2, 27 female) | Athletes had anxiety (CSAI-2R) and HRV measured prior to competition. HRV was measured 30 minutes before and 3 hours after competition and compared to swimming performance. | N/A | Polar® RS800cx<br><br>(R-R interval)<br><br>Resting (baseline pre-post competition) | **vmHRV**<br>pNN50, lnRMSSD<br><br>**HRV**<br>SDNN, LFnu, HFnu, LF/HF | Cognitive and somatic anxiety had a negative relationship with lnRMSSD. |
| Frenkel et al. (2019) | Two hundred and fourteen males participating in sports ($M_{age}$ 21.99 ± 2.95) – participants split across four experiments. | After a baseline measurement, HRV, salivary cortisol and self- reported anxiety were measured directly before a climbing challenge (participants had to jump to a rope).<br><br>(some differences exist across experiments) | Neurovisceral integration model[3], Vagal tank theory[7] | Polar RS800<br>(R-R interval)<br><br>eMotion Faros 180°<br>(ECG derived R-R interval)<br><br>Resting (baseline), resting (post event) (note some differences exist across experiments) | **vmHRV**<br>RMSSD | Only in experiment 2 was vmHRV (RMSSD) reduced across the task, however in experiment 3 and 4 there was no significant change. |
| Gantois et al. (2020) | Twenty male soccer athletes ($M_{age}$ 22.6 ± 3.3) | Within-subject design where mental fatigue was induced (15 min Stroop or 30 min Stroop or control) prior to a training match. | Neurovisceral integration model[3] | Polar® RS800cx<br><br>(R-R interval)<br><br>Resting (baseline), resting (post event, mental fatigue) | **vmHRV**<br>RMSSD, pNN50<br><br>**HRV**<br>SDNN | No differences were found between mental fatigue conditions and vmHRV and other HRV parameters prior to a training-based game. 30 minutes of Stroop was linked to worse decision making performance in game, but this was not linked to any reported HRV parameters |

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| Gross et al. (2017) | An Olympic level trap shooting athlete (45 years old) | A case study of resonant frequency breathing training across one year. | Resonance frequency model[12] | Biofeedback sessions: Nexus-10 encoder (PPG)<br>(PPG derived R-R interval)<br><br>Simulated competition: Hexoskin biometric shirt (ECG)<br>(authors reported the Hexoskin ECG data was not sufficient to derive HRV parameters)<br><br>Resting (baseline), event (breathing), event (competition) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>TP, LF%, LF (peak %TP)<br><br>(FFT) | Post intervention the client was able to enhance her HRV (TP%, LF%) above resting levels. |
| Hauer, Tessitore, Knaus and Tschan (2020) | Twelve male Lacrosse athletes ($M_{age}$ 26.8 ± 5.6) | Subjective (short recovery and stress scale, total quality recovery and RPE) and objective (HRV) measures of load and recovery were monitored across the course of a competition. | N/A | Polar RS800<br><br>(R-R interval)<br><br>Resting (baseline morning recordings) | **vmHRV**<br>RMSSD, pNN50 | Reductions in vmHRV (RMSSD and PNN50) were observed between baseline and competition, however no relationships were found between subjective markers and vmHRV. |
| Holguín-Ramírez, Ramos-Jiménez, Quezsada-Chacón, Cerveantes-Borunda and Hernández-Torres (2020) | Forty-two male football players (experimental group $M_{age}$ 16.9 ± 1.3, control $M_{age}$ 17.4 ± 1.3) | Six-week mindfulness program. RESTQ-76 and HRV were evaluated one day before competition (3rd, 6th and 8th week). | N/A | POLAR TEAM 2<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>SD1<br><br>**HRV**<br>SD2 | Six weeks of mindfulness training improved psychological variables, i.e. increase in stress-recovery balance and decrease in global stress. No effects found for vmHRV. |
| Huang et al. (2019) | Forty-six collision-contact athletes. Twenty-three concussed ($M_{age}$ 20 ± 1) and twenty three sex-matched control | Athletes had resting HRV measured followed by the 2-Back test (sustained attention and executive function). | Neurovisceral integration model[3,4] | ECG via Solar 8000i patient monitor (GE healthcare)<br><br>(ECG derived R-R interval) | **HRV**<br>HF (%) | Concussed athletes had lower HRV (HF%) power at rest than healthy controls, however concussed athletes had higher HRV (HF%) reactivity and HRV (HF%) power during the cognitive test than healthy controls. Controls outperformed concussed athletes on accuracy but not on response time. |

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| | athletes ($M_{age}$ 20 ± 1) | | | Resting (baseline), reactivity | | |
| Hunt, Rushton, Shenberger and Murayama (2018) | Seventy-six athletes from a range of sports ($M_{age}$ 19.96, 45 female) | Deep breathing vs progressive muscular relaxation influence on relaxation levels and HRV and subsequent cognitive challenge (sections of the Wechsler Adult Intelligence Scale). | N/A | Hexoskin Biometric Shirt (ECG)<br><br>(ECG derrvied R-R)<br><br>Resting (baseline), event | **HRV**<br>SDNN | Deep breathing increased HRV (SDNN) more than progressive muscular relaxation during the intervention, but this did not carry over to cognitive challenge. |
| Hutchison et al. (2017) | Twenty-six concussed athletes from a range of sports and matched controls (n. 26) ($M_{age}$ 21.0 ± 2.5, 10 female) | Athletes were monitored at three phases of concussion recovery with HRV, cortisol and psychometrics (1.Week post-concussion, 2. Resolution of symptoms, 3. Return to play). | N/A | Polar heart rate monitor<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$TPms^2$, LF/HF, RRstd, $LFms^2$ | Across the three time points the control athletes had significantly higher vmHRV ($HFms^2$) and HRV ($RR_{std}$) than concussed athletes. HRV (LF/HF) was significantly higher at the return to play phase. Total mood disturbance was found to decrease $LFms^2$, which was greater in males, but not directly linked to concussion. |
| Hynynen, Uusitalo, Konttinen and Rusko (2008) | Twelve overtrained athletes ($M_{age}$ 25± 7, 6 female) and twelve control athletes ($M_{age}$ 24 ± 5, 6 female) | Comparing autonomic responses to an active orthostatic test and Stroop test (three speeds) in overtrained athletes vs control. | Polyvagal theory[10]– in discussion | Polar Electro<br><br>(R-R Interval)<br><br>Resting (baseline), resting (standing) event (Stroop), resting (relaxation) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>$TPms^2$, $LFms^2$<br><br>(AR) | Overtrained athletes made more mistakes in the Stroop task than the control. vmHRV ($HFms^2$, RMSSD) and HRV ($TPms^2$ , LF) decreased significantly from slow to fast speed Stroop in the control but not in overtrained athletes. A negative relationship was found between mistakes made and HRV ($TPms^2$) during relaxation (all subjects). |
| Iellamo, Pigozzi, Parisi and Di Salvo (2003) | Seven elite pentathlon athletes ($M_{age}$ 26.7 ± 1.3, 4 male) | Measured HRV and cortisol on a normal training day and on a day of competitive selection to determine changes in stress, above the stress caused by physical exertion. | N/A | ECG from a chest lead (HPM1403A, HPM1401A, HPM1402A)<br><br>Resting (baseline morning and evening) | **vmHRV**<br>HF $ms^2$<br><br>**HRV**<br>LF $ms^2$, LF/HF $ms^2$ , LFnu, HFnu, LF/HFnu<br><br>(AR) | There were no differences in any vmHRV ($HFms^2$) and other HRV parameters measurements across a training day or competitive selection day. |
| Kim, Hwang, Park, Cho and Kim (2019) | Eight elite wheelchair shooting athletes | Baseline HRV taken followed by 1.15hr of shooting split into 6 sets of 10. After each | N/A | Polar HR belt (Polar-R5800)<br><br>(R-R interval) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV** | HRV (LF/HF) was significantly lower at rest when compared to practice and actual shooting. vmHRV and other HRV |

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| | (Age range 31-56, 3 female) | set, flow and shooting performance were recorded. | | Resting (baseline), event (during shooting) | SDNN, LFms$^2$, LF/HF | parameters were not related to shooting performance or flow state. |
| Korobeynikov, Mazmanian, Korobeynikova and Jagiello (2011) | Twenty-seven wrestlers ($M_{age}$ 22.7 ± 2.6, 8 female) | Assessing motivation, simple reaction time, choice reaction time, and HRV responses. | N/A | Cardio+<br><br>(ECG derived R-R interval)<br><br>Resting (baseline) | **HRV**<br>SDNN, LF/HFnu, Stress index (SI) | No relationships between motivation and HRV markers. |
| Laborde, Brull, Weber and Anders (2011) | Thirty male handball players ($M_{age}$ 22.5 ± 1.7) | Players trait emotional intelligence was measured, following this they were exposed to lab stressors (e.g. negative imagery, crowd noise) whilst HRV was measured. | Neurovisceral integration model[3] | Nexus 4<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), resting (post manipulation) | **vmHRV**<br>RMSSD, pNN50<br><br>**HRV**<br>LF/HF, SDNN, LFnu, HFnu | Trait emotional intelligence (wellbeing) was found to predict baseline HRV (LF/HF), while trait emotional intelligence (emotionality) predicted HRV (LF/ HF) post stressor. |
| Laborde, Lautenbach and Allen (2015) | Ninety-six male sport science students and actively competing in sport ($M_{age}$ 25.49 ± 6.41) | Assessing coping-related variables and HRV under pressure during a visual search task. | Neurovisceral integration model[3,4,5] | Nexus 4 and Biotrace software<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, reactivity | **HRV**<br>HFnu<br><br>(FFT) | Trait emotional intelligence (wellbeing) was positively associated to resting HRV (HFnu). Trait emotional intelligence (emotionality) and coping effectiveness positively influenced task HRV (HFnu). Threat appraisal negatively affected task HRV (HFnu) and was associated to greater reduction in HRV (HFnu), reactivity HRV (HFnu) not associated to performance. |
| Lagos et al. (2008) | Case study of a fourteen year old golf athlete | Ten week slow-paced breathing biofeedback intervention comprising of four tasks (and four HRV measures), in each session the POMS and CSAI-2 were measured. The athlete recorded their weekly golf scores. | Resonance frequency model[13] | A J&J Engineering (Poulsbo, WA) I-330 DSP-12 physiograph<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (Biofeedback) | **vmHRV**<br>HFms$^2$<br><br>**HRV**<br>TP ms$^2$, LFms$^2$ | HRV (LF and total power) increased during slow-paced breathing with biofeedback and across all four sessions suggest baroreflex gain. HRV (HF) decreased during slow-paced breathing with biofeedback but increased at baseline accumulatively across the intervention. |
| Landolt et al. (2017) | Thirty-two professional jockeys | Jockeys were assessed across two points in a competitive season. | N/A | Five-lead ambulatory digital ECG recorder (AR12plus) | **HRV**<br>LF/HF | After bootstrapping a lower mean HRV (LF/HF) ratio was linked to the association between work related stress and decision |

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| | (Males 14, $M_{age}$ 18.1 ± 1.5 and females 18, $M_{age}$ 19.9 ± 2.3) | Work related stress, physiological stress and cognitive performance measured. | | (ECG derived R-R interval)<br><br>Resting (baseline), event (during stressor and cognitive task) | (FFT)<br><br>(natural log transform) | making (slower processing speed and choice reaction time). |
| Loizou and Karageorghis (2015) | Fifteen male athletes ($M_{age}$ 26.3 ± 2.8) | Exposed to four different conditions (including video, music and motivational prompts) prior to a maximal anaerobic test (Wingate). | N/A | PowerLab 16/30 (three lead ECG)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (condition) | **HRV**<br>LFuns and HFuns | Increase in HRV (LFuns) and a decrease in HRV (HFuns) in the video-music condition when compared to the control. This was the only condition to reach significance. |
| Mamlouk, Younes, Zarrouk, Shepard and Bouhlel (2021) | One hundred and seventeen athletes (endurance = 43, power = 43, healthy untrained individuals = 38) | HRV and perceived stress were measured in each group. | N/A | Polar S-810<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>pNN50, RMSSD, SD1, $HFms^2$, $lnHFms^2$<br><br>**HRV**<br>SD2, SD1/SD2, $LFms^2$, $lnLFms^2$, LF/HF | Individuals with lower perceived stress had higher vmHRV (pNN50, RMSSD, SD1, $lnHFms^2$) when compared to those with high perceived stress. In power athletes only, a negative correlation existed between perceived stress and vmHRV (RMSSD, $lnHFms^2$). |
| Mateo, Blasco-Lafarga, Martínez-Navarro, Guzmán and Zabala (2012) | Eleven male cyclists ($M_{age}$ 19.3 ± 2.1) | Anxiety (CSAI-2) and HRV were measured in resting state and prior to a simulated competition and real competition. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8], Polyvagal theory[6,14,15,16] | Polar RS800 HR monitor<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN, lnLF% and lnHF%, LF/HF, α1, SampEn<br><br>(SampEn is the negative natural logarithm) | All HRV indices besides lnLF were altered from resting baseline to both competitive days. In the first competitive day, vmHRV (RMSSD) and HRV (lnHF%, SDNN, lnLF%) were decreased and LF/HF increased. There were significant differences in anxiety between training and competition, but only α1 and somatic anxiety in resting competition (day one) were correlated. |
| Matylda et al. (2020) | Thirty-seven male rugby athletes ($M_{age}$ 24.0 ± 4.6) | Baseline cardiovascular measures taken (HR, HRV, BP) and Pain catastrophizing scale and state-trait anxiety inventory. Athletes | N/A | Nexfin®-System<br><br>(R-R interval)<br><br>Resting (baseline), event (cold pressor | **HRV**<br>SDIBI (standard deviation of the interbeat interval)<br>Note: same as SDNN | A significant increase in SDIBI was found during the cold pressor task. |

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| | | then completed a cold pressor task and recovery was measured. | | task), resting (post event) | | |
| Móra et al. (2022) | Sixty-three male soccer players ($M_{age}$ 25.14 ± 5.81) | HRV and blood pressure taken before physical and psychological stress tests and 30 minutes after. | N/A | 12 lead ECG (brand not named)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline, resting (post task) | **vmHRV**<br>pNN50, RMSSD<br><br>**HRV**<br>SDNN, TP, VLF%, LF%, HF%, LF/HF | vmHRV (RMSSD, pNN50) and HRV (VLF%, HF%, LF/HF) significantly decreased after the psychological stress test. |
| Morales et al. (2013) | Twenty-four judo athletes (national 14, $M_{age}$ 23.35 ± 2.11 and international 10, $M_{age}$ 24.10 ± 1.78, 10 male). | Anxiety (CSAI-2R) and HRV measured the morning of an official competition and an un-official (friendly) competition. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8] | Polar S810<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, pNN50, HFms$^2$<br><br>**HRV**<br>STDRR,VLFms$^2$, LFms$^2$, LF/HF, SD1, SD2, α1, α2<br><br>(FFT) | International standard athletes had higher vmHRV (RMSSD, pNN50, SD1, HFms$^2$) and HRV (STDRR, SD2) was higher in unofficial competition. HRV (LF/HF ratio) was higher in national athletes and official competition.<br><br>Correlations showed a negative relationship between somatic anxiety and vmHRV (RMSSD, SD1) and HRV (SD2, α1, α2), the same relationship was found for cognitive anxiety and vmHRV (RMSSD, NN50, HFms$^2$, SD1) and HRV (SD2, α1, α2). A positive correlation was found between cognitive anxiety and LF/HF ratio. There was a positive relationship between self-confidence and vmHRV (RMSSD, pNN50) and HRV (α2). |
| Morales, Roman, Yáñez, Solana-Tramunt, Álamo and Fíguls (2019) | Sixteen professional female soccer players ($M_{age}$ 23.25 ± 5.07) | Players underwent pre and post-season screening (6 weeks apart). Measures used included REST-Q, HRV and physical tests i.e. YoYo. | N/A | Polar RS810<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN, LFnu, HFnu, LF/HF<br><br>(FFT) | Pre vs post comparison found a decrease in HRV (HFnu) and increase in HRV (LFnu and LF/HF). vmHRV (RMSSD) was positively correlated to specific stress, general recovery and specific recovery and negatively correlated to general stress. HRV (LF/HF, HFnu) were positively correlated to specific recovery, stress, and general stress. Finally HRV (LFnu) was positively correlated to specific stress. |
| Mosley, Laborde and Kavanagh (2017) | Fifty-one participants actively | Participants competed in a dart throwing task (low and high | Neurovisceral integration model[3,5] | eMotion Faros 180 | **vmHRV**<br>HFms$^2$ | In both the low and high pressure condition reactivity and recovery vmHRV (HFms$^2$) was predicted by resting levels. vmHRV |

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| | competing in a range of sports ($M_{age}$ 24.9 ± 7.7, 21 female) | pressure). HRV and coping-related variables measured (i.e. trait emotional intelligence, demand and resource appraisal). | | (ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event), reactivity, recovery | (FFT)<br>(Log transformed) | ($HFms^2$) recovery in high pressure was increased by movement reinvestment scores.*<br><br>*See results from Mosley, Laborde and Kavanagh (2019) |
| Mosley, Laborde and Kavanagh (2018a) | Forty-nine participants actively competing in a range of sports ($M_{age}$ 24.1 ± 6.5, 21 male) | Participants competed a working memory task (low and high pressure). HRV and coping related variables measured (i.e. trait emotional intelligence, demand and resource appraisal). | Neurovisceral integration model[3,5] | eMotion Faros 180<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event), reactivity, recovery | **vmHRV**<br>$HFms^2$<br><br>(FFT)<br>(log transformed) | Task and post task vmHRV ($HFms^2$) were both predicted by resting levels in low and high pressure. In the low pressure condition vmHRV ($HFms^2$) recovery was predicted by decision reinvestment. In the high pressure condition working memory performance was predicted by lower vmHRV ($HFms^2$). |
| Mosley, Laborde and Kavanagh (2018b) | Thirty-eight prone rifle shooting athletes ($M_{age}$ 55 ± 14.8, 8 female) | Shooting athletes took part in a simulated competition (low and high pressure). HRV and coping related variables measured (i.e. trait emotional intelligence, demand and resource appraisal). | Neurovisceral integration model[3,5] | eMotion Faros 180°<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post task), reactivity, recovery | **vmHRV**<br>$HFms^2$<br><br>(FFT)<br>(Log transformed) | Task and post task vmHRV ($HFms^2$) were both predicted by resting levels in low and high pressure. vmHRV ($HFms^2$) reactivity was predicted by resting vmHRV ($HFms^2$) and self-control (trait EI) in both conditions. In the low pressure condition, shooting score was predicted by experience and post-task vmHRV ($HFms^2$). In the high pressure condition vmHRV ($HFms^2$) recovery and emotionality predicted shooting scores. |
| Neumann and Thomas (2009) | Fifty-two golfers of differing experience (Novice $M_{age}$ 21.35 ± 6.02, Experienced $M_{age}$ 25.94 ± 6.46, Elite $M_{age}$ 22.58 ± 4.14, 17 female) | Golfers had 10 practice putts followed by 20 putts at the hole. | N/A | PowerLab (ADInstruments, Sydney) Model 4/20 physiological data acquisition system<br><br>(ECG derived R-R interval)<br><br>Event | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$VLFms^2$, $LFms^2$<br><br>(Log transformed) | Elite and experienced golfers had better putting performance than novice. vmHRV ($HFms^2$) and HRV ($LFms^2$) was lower in the novice group when compared to the experienced group. On further analyses, it was confirmed that HRV ($LFms^2$) was lower in novice than elite and experienced golfers. The elite and experienced groups did not differ in vmHRV ($HF ms^2$) nor in HRV ($LF ms^2$). |
| Nicolas, Vacher, Martinent and Mourot (2019) | Eleven national level swimmers ($M_{age}$ 17.09 ± 1.64, 1 female) | HRV and REST-Q collected at the beginning and at the end of a two-week | N/A | Suunto t6 heart rate monitor<br><br>(R-R Interval) | **vmHRV**<br>RMSSD<br><br>(Natural log transform) | No association was found between RESTQ-36-R-Sport subscales and vmHRV (RMSSD). |

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| | | tapering period before a major competition. | | Resting (baseline) | | |
| Oliveira-Silva, Silva, Cunha and Foster (2018) | Twelve cyclists ($M_{age}$ 27.5 ± 6.5) | Cyclists baseline HRV and physical fitness was measured in a lab based setting. The second assessment was 30 minutes before the last stage of a regional competition (HRV and CSAI-2 measured). | N/A | RS800 Polar Electro (validated against electrocardiographic data, ICC > 0.8)<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, SD1<br><br>**HRV**<br>SDNN, lnLFuns, lnHFuns, LF/HF, SampEn, α1 | On the day of competition there was a significant increase in HRV (SDNN) from baseline. No relationship between HRV parameters and anxiety. |
| Ortega and Wang (2018a) | Fifty air rifle shooters ($M_{age}$ 14.98 ± 1.39, 17 males) | A single case design (A-B-A) for intervention training. The intervention group received slow-paced breathing biofeedback training while the control group continued with normal shooting training. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8], Polyvagal theory[16] | Polar H7 EKG Belt<br><br>(R-R Interval)<br><br>Resting (baseline pre and post intervention) | **HRV**<br>SDNN | The intervention group had significantly higher HRV (SDNN) post intervention than the control group. |
| Ortega and Wang (2018b) | Sixty-one shooters (air pistol and air rifle, 24 males) (21 novice $M_{age}$ 13.42 ± 0.75, 19 intermediate $M_{age}$ 15.16 ± 0.60, 21 advanced $M_{age}$ 21.71 ± 7.66) | Shooters were instructed to breathe slowly and relax as they normally would before a shot in this time. HRV, TOPS and self-efficacy was measured. Following this, participants completed normal competitive procedures. | Polyvagal theory[10], Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8] | Thought Technology's ProComp Infiniti and Polar H7 EKG Belt<br><br>(R-R Interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN | Self-efficacy and shooting score were positively correlated with vmHRV (RMSSD). No differences in vmHRV (RMSSD) and HRV (SDNN) across experience levels. |
| Ortigosa-Marquez, Reigal, Portell, Morales-Sanchez and Hernadez-Mondo (2017) | Nine swimmers, 7 girls ($M_{age}$ 11.5 ± 1.5 years) and two boys ($M_{age}$ 11.5 ± 2.1) | Three sessions over three weeks measured HRV, POMS, Rosenberg Self-Esteem Scale, and the Sleep Quality Scale and swimming performance. | N/A | RS800CX and a Polar WearLink W.I.N.D transmitter<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>lnRMSSD, lnPNN50, lnSD1<br><br>**HRV**<br>LnHFuns, LnVLFuns<br><br>(Log transformed) | Anxiety and confusion were inversely correlated with HRV (lnHFuns). HRV (lnVLF) was positively correlated with anxiety and negatively correlated with vigor. No relationships between vmHRV or other HRV parameters with sleep and self-esteem. Negative correlation between vmHRV (lnRMSSD, pNN50, SD1) and swimming performance. |

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| Park, Hwang and Lee (2020) | Eight racket sport athletes ($M_{age}$ 28.37 ± 4.02 years, 3 male) | Ten weeks of slow-paced breathing biofeedback training sessions were conducted. Pre and post HRV measured. | Resonance frequency model[17] | ProComp Infinit-8 Channel Biofeedback System<br><br>(PPG derived R-R interval)<br><br>Resting (baseline pre and post training) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN, LFuns, HFuns, LF/HF | vmHRV (RMSSD) and other HRV parameters (SDNN, HFuns, LFuns and LF/HF) increased after the slow-paced breathing biofeedback intervention |
| Parrado, Cervantes, Pintanel, Rodas and Capdevila (2010) | Eight international male hockey players ($M_{age}$ 23.1 ± 1.4) | Perceived tiredness measured on arrival to the hockey world cup. The morning prior to the semi-final HRV and anxiety (CSAI-2) was taken. | N/A | Omega Wave Sport System<br><br>(ECG derived R-R interval)<br><br>Resting (baseline supine) | **vmHRV**<br>RMSSD, pNN50<br><br>**HRV**<br>LF/HF | Negative correlation between perceived tiredness and vmHRV (RMSSD and PNN50). Whereas the opposite relationship was found for HRV (LF/HF). Somatic anxiety was shown to have a positive relationship with HRV (LF/HF). |
| Patil, Mullur, Khodnapur, Dhanakshirur and Aithala (2013) | Twenty-four junior cyclists ($M_{age}$ 23.1 ± 1.4) | Subjects split into experimental and control group. Experimental group had yoga every day for four weeks, LF/HF was taken pre and post intervention. | N/A | Four channel digital polygraph<br><br>(ECG derived R-R interval)<br><br>Supine baseline | **HRV**<br>LFnu, HFnu, LF/HF | Post yoga intervention HRV (HFnu and LFnu) increased significantly while HRV (LF/HF ratio) decreased. Whereas in the control group a decrease in HRV (HFnu) was found. |
| Paul, Garg and Sandhu (2012) | Thirty basketball players ($M_{age}$ 21.70 ± 2.71, 14 female) | Players were split into experimental (10 days of slow-paced breathing biofeedback), placebo (motivational videos) and control (no treatment) groups. Concentration, reaction time, and HRV were taken pre, post and at one month follow-up. | Resonance frequency model[13] | Biograph Procomp Infiniti 5.0<br><br>(ECG derived R-R interval)<br><br>Resting (baseline pre and post intervention) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$TPms^2$, LF $ms^2$ | At post training and follow up HRV (TP and $LFms^2$) increased whereas vmHRV ($HFms^2$) decreased. However, vmHRV ($HFms^2$) increased across the sessions for the experimental group. |
| Paul and Garg (2012) | Thirty basketball players ($M_{age}$ 21.13 ± 2.82, 13 female) | Players were split into experimental (10 days of slow-paced breathing biofeedback), | Resonance frequency model[13] | Biograph Procomp Infiniti 5.0 | **vmHRV**<br>$HFms^2$<br><br>**HRV** | At post training and follow up HRV (TP and $LFms^2$) increased whereas vmHRV ($HFms^2$) decreased. However vmHRV ($HFms^2$) increased across the sessions for |

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| | | placebo (motivational videos) and control (no treatment). Anxiety, self-efficacy, basketball tests and HRV were taken pre, post and one month follow up. | | (ECG derived R-R interval)<br><br>Resting (baseline pre and post intervention) | TP$ms^2$, LF $ms^2$ | the experimental group. Trait and state anxiety were lowered in the experimental group as well as basketball performance. |
| Paula, Paza, Peirozan and Stefanello (2016) | Thirty-six male basketball players ($M_{age}$ 14.0 ± 1.0) | The evening prior to competition (or the day of if not available) HRV was measured along with mood (BRUMS), anxiety (CSAI-2R) and confidence (SCI). | Resonance frequency model[12] | CardioEmotion®<br><br>(R-R Interval)<br><br>Resting (baseline) | **HRV**<br>No coherence (0.04hz), almost coherent (0.1hz). cardiac coherence (0.5hz) | No relationship found between HRV and mood states, pre competitive anxiety or self-confidence. |
| Penna et al. (2018) | Sixteen swimming athletes ($M_{age}$ 15.45 ± 0.51) | Within-subject design in which swimmers completed two time trials preceded by a treatment - a control (neutral video) or a Stroop task. Perception of mental fatigue, performance, and HRV were measured. | N/A | Polar® H7<br><br>(R-R Interval)<br><br>Resting (baseline), resting (Post swim, post treatment) | **vmHRV**<br>RMSSD, HF $ms^2$<br><br>**HRV**<br>VLF$ms^2$, LF$ms^2$, LF/HF, LFnu, HFnu<br><br>(FFT, natural log) | Perceptions of induced mental effort did not influence HRV. Further analysis showed RR and vmHRV (RMSSD) were lower at post-swim and post-treatment. LF/HF was higher at post-swim compared to post treatment. |
| Perkins, Wilson and Kerr (2001) | Twenty-eight elite level athletes ($M_{age}$ 20.3 ± 5.5, 6 females, plus 28 sex and age matched recreational athlete controls) | Athletes were induced into a telic and para-telic state through imagery which was followed by a hand-grip test. | Polyvagal theory[18]– in discussion | MacLab Physiological Data Acquisition System<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (script) | **vmHRV**<br>RSA - Peak to trough method | vmHRV (peak to trough) was higher in paratelic condition compared to the telic condition. vmHRV (RSA peak to trough) was also found to be higher in the neutral condition than in the telic condition. |
| Perry, Hansen, Ross, Montgomery and Weinstock (2019) | Twenty male collegiate soccer players ($M_{age}$ 19.65 ± 1.04) | A stress assessment protocol was used consisting of the following: baseline, cognitive stressor (counting task), recovery, physical | Resonance frequency model[13] | emWave Pro by HeartMath®<br><br>(PPG derived R-R interval) | **HRV**<br>Coherence and amount of time spent in coherence (basic–good, good, very good, excellent). | HRV (coherence score) was lower during the cognitive stressor than the following recovery, the same pattern was found for the sport specific stressor but not for the physical stressor. |

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| | | stressor (cold pressor), recovery, sport specific stressor (revisiting a stressful time in sport), recovery. | | Resting (baseline), event, Resting (post stressor) | | |
| Piatrikova et al., (2021) | Ten swimmers ($M_{age}$ 16 ± 1, six male) | HRV recordings, subjective wellbeing and session intensity measures were taken daily across a short-course season. | N/A | HRV4Training<br><br>(PPG derived R-R interval)<br><br>Resting (baseline morning) | **vmHRV**<br>RMSSD | Variance predicted in vmHRV (RMSSD) responses was improved when wellbeing variables were added to the model. |
| Portillo and Rodriguez (2020) | Thirteen ski mountaineer athletes, 9 males ($M_{age}$ 23 ± 1.5) and 4 females ($M_{age}$ 23.5 ± 1.3) | Across a three race national competition (included two days pre and post), athletes HRV and subjective measures (i.e. fatigue, RPE, health status) were measured. | N/A | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline morning) | **vmHRV**<br>RMSSD, $HFms^2$, pNN50, SD1<br><br>**HRV**<br>SDNN, NN50nu, $TPms^2$, $VLFms^2$, $LFms^2$, LFnu, HFnu, LF/HF, SD2<br><br>(Both AR and FFT presented) | No relationships were found between HRV and perceptual indices with performance. |
| Rollo, Tracey and Prapavessis (2017) | Twenty-eight injured athletes ($M_{age}$ = 20.82 ± 3.41, 19 male) | Injured participants split into slow-paced breathing with biofeedback experimental (3 weeks of slow-paced breathing with biofeedback), slow-paced breathing with biofeedback placebo (3 weeks of slow-paced breathing with biofeedback – not informed to maximise HRV) and control group (no training). Measures taken across 4 weeks including HRV, psychological | Resonance frequency model[12,13] | Power Lab 26T bio-feedback unit with LabChart® 7.0 software<br><br>(ECG derived R-R)<br><br>Resting (baseline), event (during slow-paced breathing with biofeedback) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$LFms^2$, $TPms^2$ | Increase in HRV ($LFms^2$) in the experimental group at rest as a result of slow-paced breathing with biofeedback. Negative correlations were found between psychological outcomes of injury and HRV (i.e., $LFms^2$, $TPms^2$ paced and reorganisation, and TPms2 paced and helplessness). |

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| | | reaction to injury and pain catastrophising. | | | | |
| Rusciano, Giuliano and Stoianov (2017) | Twenty male professional soccer players (Experimental group $M_{age}$ 30.0 ± 3.8, control $M_{age}$ 30.7 ± 4.3) | Athletes were screened pre and post-intervention (either a 15 session slow-paced breathing with biofeedback intervention or control). Screening involving a Stroop task, visual search task and recorded number of training days. | Polyvagal theory[7], Neurovisceral integration model[3,4,5], Resonance frequency model[13] | Nexus 10 Mark II hardware and Biotrace1 commercial software<br><br>(PPG derived R-R interval)<br><br>Resting (baseline), event (stress), resting (post event) | **HRV**<br>LF%<br><br>(FFT) | Resting HRV (LF%) increased from pre to post-intervention in the experimental group only. |
| Sartor, Vailati, Valsecchi, Vailati and La Torree (2013) | Six male gymnasts ($M_{age}$ 16 ± 2) | Morning measurements of HRV were taken across a training period. RPE and Fosters index (measure of psychological complaints). | N/A | Polar, RS800CX<br><br>(R-R interval)<br><br>Resting (baseline supine and sitting morning measurements) | **vmHRV**<br>SD1<br><br>**HRV**<br>LF%, HF%, LF/HF, SDNN | HRV (HF% and SD1) were found to be correlated with RPE the previous day but not with the Fosters index (measure of psychological complaints). |
| Sartor et al. (2017) | Ten male gymnasts ($M_{age}$ 16 ± 2) | Gymnastics were monitored 5 days prior and after an important competition. During this time HRV, cognitive performance (Stroop), sleep and pain were measured. | N/A | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline), event (baseline task, cognitive task) | **vmHRV**<br>RMSSD, lnRMSSD, pNN50, $HFms^2$, SD1<br><br>**HRV**<br>SDNN, HF%, lnHF, HF nu, LF%, $LFms^2$, lnLF, LF nu, LF/HF, SD2 | vmHRV (pNN50) and HRV (HF%), were significantly higher post-competition when compared to pre-competition. Significant positive correlation between number of errors and SD2. |
| Shaw, Zaichkowsky and Wilson (2012) | Eleven female gymnasts ($M_{age}$ 19.9 ± 0.39) | Athletes underwent a 10-week slow-paced breathing biofeedback and neurofeedback intervention. Pre and post-balance beam performances were recorded and judged, as well as being rated subjectively by the athletes. | Resonance frequency model[13] | Thought Technology (TT) Procomp Infiniti<br><br>(PPG derived R-R interval)<br><br>Resting (baseline pre and post intervention) | **HRV**<br>SDNN, HF%, LF%, VLF% | No significant changes in HRV pre-post intervention. |

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| Souza et al. (2019) | Fifty-four male athletes (18 Canoe $M_{age}$ 18.9 ± 1.35, 18 Running $M_{age}$ 21.12 ± 8.73, 18 Jjiu Jitsu $M_{age}$ 21.29 ± 4.50) | A two-part study consisting of measurements of anxiety (CSAI-2), cortisol and HRV prior to training and competition. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[8] | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline supine) | **HRV**<br>LF/HFnu<br><br>(FFT) | LF/HF ratio was found to be higher prior to competition than training, however no differences between athlete type were found. A significant positive correlation between LF/HF and cortisol was found pre training and pre competition. No relationship between LF/HF and anxiety was found. |
| Thornton, Sheffield and Baird (2019) | One hundred and twenty university athletes ($M_{age}$ 21.1 ± 3.8, 57 female) Athletes were split into experienced contact, novice contact and novice non-contact. | Athletes were split into either a pain condition or no pain under either challenge or threat instructions. In the pain condition athletes were subjected to pain whilst performing a motor task (target throwing task). | N/A | ithlete™<br><br>(R-R interval)<br><br>Resting (baseline), event (post instructions) | **HRV**<br>RMSSD index<br><br>(presented as a number between 1-100 from the ithlete™ device) | HRV (RMSSD index) was significantly higher in the challenge group compared to the threat group. Both groups of contact athletes had higher HRV (RMSSD index) and cognitive appraisal in the pain condition compared to non-contact athletes (this was not affected by the challenge or threat manipulation). |
| Tibana et al. (2019) | Female crossfit athlete (34 years old) | HRV, training load and wellbeing measures were taken across a season (38-week period). | N/A | HRV4training<br><br>(PPG derived R-R)<br><br>Resting (baseline supine waking) | **vmHRV**<br>LnRMSSD<br><br>(Log transformed) | No correlations found between subjective markers of recovery (i.e., wellbeing, mood, stress) and vmHRV (LnRMSSD). |
| Vacher, Martinent, Mourot and Nicolas (2018) | Twenty-one male swimmers ($M_{age}$ 17.80 ± 1.17) | Athletes monitored over three months across four time points. Psychological (REST-Q, perceived control) and physiological (HRV) measures of recovery taken. | N/A | Suunto t6 Memory Belt<br><br>(R-R interval)<br><br>Resting (baseline period of recovery following exercise) | **vmHRV**<br>RMSSD, pNN50, SD1<br><br>**HRV**<br>LFuns, HFuns, LF/HF, SD2, SD1/SD2 | Perceived control was positively associated to vmHRV (pNN50) and perceived recovery. |
| Vacher, Filaire, Mourot and Nicolas (2019) | Fifteen swimming athletes ($M_{age}$ 17.8 ± 1.1, nine male) | Athletes monitored over 12 weeks (rest, preparation, and taper) multiple measures of physiological, psychological and performance markers (i.e. HRV, swim speed, REST-Q, Sport | N/A | t6 Suunto Memory Belt<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD | vmHRV (RMSSD) was positively related to external training load, but no significant relationship was found with the perceived internal training load as determined through rate of perceived exertion). |

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| | | emotion questionnaire, cortisol). | | | | |
| Vaz, Ribeiro, Pinheiro and Del Vecchio (2019) | Fifteen football players ($M_{age}$ and SD not reported) | Technical (soccer skills test), physiological (HRV), and psychological data (POMS/ DALDA) was collected after two friendly matches. | | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline supine) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>LFuns, HFuns | HRV parameters were not associated to performance or to the psychological variables measured. |
| Yen (2012) | Twenty-four male rugby athletes ($M_{age}$ 22.7 ± 2.3) | Athletes went through an eight week cardiovascular endurance training programme, with five tests throughout (including HRV and POMS). | N/A | Electrocardiograms (SSIC, Enjoy Research Inc)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline supine) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$LFms^2$, LF/HF<br><br>(AR)<br><br>(Log transform) | Measures of HRV ($HFms^2$, $LFms^2$) and HRV (LF/HF) were significantly correlated with elements of the POMS before, during and after the training. |
| You, Laborde, Salvotti, Zammit, Mosley and Dosseville (2021) | Twenty-four athletes ($M_{age}$ 22.5, range -26) | In a within-subject design athletes completed a single session of slow-paced breathing with HRV measures during, directly after, and 60 minutes post. This was compared to a TV control condition. | Neurovisceral integration model[3], Resonance frequency model[14], Vagal tank theory[7] | Faros 180° (Bittum)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline, slow-paced breathing, directly after, 60 mins post) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>SDNN, $LFms^2$, LF/HF<br><br>(FFT) | vmHRV (RMSSD) was higher during the slow-paced breathing intervention compared to control, while no differences were found immediately after intervention or 60min post-intervention). In the slow-paced breathing condition, vmHRV (RMSSD) was higher during the intervention in comparison to resting measurement, immediately after the intervention and 60min post-intervention. |
| You et al. (2021) | Sixty-one athletes ($M_{age}$ 22.1, range 18-30, 25 female) | A five minute HRV baseline was completed, followed by five minutes of slow paced breathing or control (counterbalanced), followed by five minutes recovery, followed by ratings of perceived stress, emotional arousal and valance. | Neurovisceral integration model[3,5,19], Vagal tank theory[7] | Faros 180° (Bittum)<br><br>(ECG derived R-R interval) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>SDNN, $LFms^2$, LF/HF | vmHRV (RMSSD) was higher in the slow paced breathing condition compared to the resting control. During slow paced breathing vmHRV (RMSSD) was higher than baseline and recovery. |

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Table 4: Exercise Psychology Papers

| Study | Participants | Protocol | HRV theory reported | HRV measurement | HRV Parameters Reported | Main Findings |
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| Albinet, Boucard, Boquet and Audiffren (2010) | Twenty-four sedentary older adults ($M_{age}$ 70.7 ± 4.2, 13 women) | Aerobic exercise program VS stretching program (three times a week for 12 weeks) influence on HRV and cognitive performance (Wisconsin card sorting task). | Neurovisceral integration model[1,2] | Polar Wearlink Wind transmitter belt<br><br>(R-R interval)<br><br>Resting (baseline), resting (post-test) | **vmHRV**<br>RMSSD, HFms$^2$<br><br>**HRV**<br>SDNN, LFms$^2$,<br><br>(FFT, Log transformed) | The aerobic group had a significant increase in vmHRV (RMSSD, HFms$^2$), and HRV (SDNN) and decreased errors in the cognitive test from pre-post test. The stretching group had a significant decrease in vmHRV (RMSSD, HFms$^2$) and SDNN and made more errors in the cognitive test from pre-post test. |
| Albinet, Abou-Dest, André and Audiffren (2016) | Thirty-six healthy older adults (Swimming $M_{age}$ 67 ± 5, Stretching $M_{age}$ 66 ± 5) | Aqua aerobics and swimming training VS stretching (21 weeks). Pre and post intervention HRV, VO$^2$, psychological questionnaires and cognitive tests were completed. Mid way (10 weeks) VO$^2$ and cognitive tests completed. | Neurovisceral integration model[1,2] | Polar Wearlink Wind transmitter belt<br><br>(R-R interval)<br><br>Resting (baseline), resting (post test) | **vmHRV**<br>RMSSD, HFms$^2$<br><br>**HRV**<br>LFms$^2$,<br>HF/(LF+HF) nu<br><br>(FFT, Log transformed) | The swimming group had significant improvements in vmHRV (RMSSD, HFms$^2$) and HRV (HF/(LF+HF nu)) and executive performance (Stroop and Verbal running tasks) from pre to post intervention. Only Stroop performance improvement from pre-post was linked to vmHRV (RMSSD, HF ms$^2$ ). |
| Albracht-Shulte and Robert-McComb (2018) | Forty healthy female college students ($M_{age}$ 20.18 ± 1.97) | Randomized repeated-measures crossover clinical trial. Yoga vs. seated rest as a mean to reduce anxiety and act as a buffer against emotional stimuli. | N/A | ProComp Infiniti System with Bio-graph software version 6.0<br>(Not stated if ECG or just R-R interval data, used electrodes)<br><br>Resting (baseline), event (post condition, post exposure) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>LFnu, HFnu | Exposure to emotional stimuli post-exposure increased vmHRV (RMSSD) and LFnu. |
| Alderman and Olson (2014) | Fifty-six healthy undergraduate students | Participants completed the Eriksen flanker task followed by a maximal aerobic fitness test. | Neurovisceral integration model[1,2,3] | ioPac MP150 and MindWare Impedance Cardiograph equipment | **vmHRV**<br>HFms$^2$<br><br>**HRV** | Higher task vmHRV (HFms$^2$) positively correlated with faster reaction times for congruent and incongruent stimuli. Fitter individuals had higher vmHRV (HFms$^2$) |

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| | ($M_{age}$ 21.0 ± 1.2, 27 female) | | | (ECG derived R-R interval)<br><br>Resting (baseline), event | LFms², LF/HF<br><br>(natural log transform, FFT) | during the task than lower fit. However, vmHRV (HFms²) was not associated to greater cognitive performance. |
| Barreto-Silva, Bigliassi, Chierotti and Altimari (2018) | Twenty healthy adults ($M_{age}$ = 25.5 ± 1.2) | Participants completed a 6-minute cycle at 70% RPM in three audio-visual conditions (pleasant, unpleasant and neutral). | N/A | Polar RS800<br><br>(R-R interval)<br><br>Resting (baseline), event | **HRV**<br>LFuns and HFuns | Differences between HRV (LFuns) existed between pleasant and unpleasant stimuli conditions and between pleasant and neutral stimuli within the last ten minutes. During the pleasant stimuli HRV (HFuns) increased. |
| Benzing V, Heinks T, Eggenberger N, Schmidt M (2016) | Sixty-five male adolescents ($M_{age}$ = 14.51 ± 1.08) | Participants completed pre and post executive function tests (via the Delis-Kaplan Executive Function systems), in one of three conditions of gamified workouts (Shape up, running and control). | N/A | Polar Team2 Pro system<br><br>(R-R interval)<br><br>Resting (baseline), event, resting (post task) | **vmHRV**<br>RMSSD | The physically active conditions resulted in a reduced vmHRV (RMSSD) post task. |
| Boutcher Nugent, Mclaren and Weltman (1998) | Thirty collegiate men (Trained $M_{age}$ = 20.80 ± .61, untrained low HR $M_{age}$ = 22.40 ± .72, control $M_{age}$ = 21.92 ± .74) | Participants had $VO_2$ max tested. Two weeks later they underwent two stress tasks: 1. Mental arithmetic and 2. Stroop. | N/A | Grass physiograph, Model 7D<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event) | **vmHRV**<br>HFms²<br><br>**HRV**<br>MFms² (medium frequency was determined between 0.07 and 0.11 Hz)<br><br>(Natural transform) | Trained and low HR had higher vmHRV (HFms²) at rest than the control group. Trained and low HR groups also demonstrated greater reductions in HRV (MFms²) and vmHRV (HFms²) as a response to mental challenge (Stroop). |
| Cheema et al. (2013) | Thirty-seven university employed workers ($M_{age}$ = 38 ± 12, 30 women) | Yoga vs control group, 10-week lunch time intervention. Measures included HRV, anxiety, quality of life, job satisfaction. | N/A | Sphygmocor system<br><br>(ECG derived R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, pNN50, HFms²<br><br>**HRV**<br>SDNN, LFms², TP ms², LF/HF | Yoga group significantly reduced vmHRV (pNN50) and increased HRV (log LF/HF) versus the control group. State anxiety at baseline in the cohort was negatively correlated to vmHRV (RMSSD, pNN50) and all other HRV parameters. |

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| | | | | | (Log transformed) | |
| Crawford, Heinrich, Drake, DeBlauw and Carper (2020) | Fifty-five healthy participants (control $M_{age} = 24 \pm 4$, Experimental $M_{age} = 23.6 \pm 4.5$, 29 women) | Six-week exercise (control) vs HRV monitored exercise (experimental). Training was modified based on HRV differential from baseline. Motivation and fatigue measured daily on VAS scales. | Neurovisceral integration model[1,3] | HRV4Training application<br><br>(PPG derived R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>Ln RMSSD<br><br>**HRV**<br>LFnu, HFnu, LF/HF<br><br>(Log transformed) | In the control group decreased HRV (LF/HF) led to increased fatigue and decreased motivation, the opposite was observed in the experimental group. |
| da Silva et al. (2017) | Thirty-seven sedentary young adults 28 women; ($M_{age} = 25.1 \pm 4.6$) | Repeated-measures design consisting of a graded maximal exercise test on a cycle ergometer (exercise vs control), measured HRV, affective responses and inhibitory control (Stroop). | Neurovisceral integration model[2] | RS800CX training computer, Polar and Polar WearLink.<br><br>(R-R interval)<br><br>Resting (baseline), event | **HRV**<br>HFnu, LFnu, LF/HF (FFT)<br><br>(Log transformed) | All HRV variables were lower as a result of exercise. At the highest level of exercise intensity, HRV (LFnu and LF/HF) was negatively correlated to pleasure. |
| da Silva, Peixoto, Ferraro, Adamo and Machado (2020) | Thirty-six healthy women (aged 18-35) | 11 week running programme (experimental HRV guided running vs control pre-defined program). After the baseline and post intervention participants answered POMS and REST-Q. | Neurovisceral integration model[1,3] | RS800cx Polar<br><br>(R-R interval)<br><br>Resting (baseline), resting measures throughout training programme. | **vmHRV**<br>RMSSD | The vmHRV (RMSSD) running group demonstrated reduced negative mood and stress factors not observed in the control. |
| Daly, Baueister, Delaney and MacLachlan (2014) | 198 healthy participants ($M_{age} = 23.39 \pm 6.26$, 66 % female) | Self-reported health behaviours and self-control were compared to a one-day measurement of HRV and salivary cortisol. Affective measurement from the day were assessed through a day reconstruction. | N/A | Suunto Memory Belt<br><br>(R-R interval)<br><br>Event | **HRV**<br>SDNN<br><br>Baseline and a full day ambulatory measure | High levels of trait self-control were linked to high levels of HRV (SDNN) across a day measurement, HRV (SDNN) was also lower if the participants smoked. |
| de Gues, Doornen, Visser and Orlebeke (1990) | Twenty-six male sedentary students ($M_{age} = 23.7 \pm 12.5$) | Participants were split into two groups (aerobic fitness 7 weeks vs | N/A | FM Impedance Cardiograph (model 100) | **vmHRV**<br>RSA (peak to trough method) | vmHRV (RSA, peak to trough method) reduced during memory and reaction tasks, but the decrease was smaller in fitter subjects. |

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| | | control) $V0_2$ was initially taken. Anxiety was measured (STAI) followed by three stress tests (memory, reaction time, cold pressor task). This was repeated post exercise intervention. | | (ECG derived R-R interval)<br><br>Resting (baseline), events, resting (post events), reactivity, recovery | | |
| De Oliveria Matos, Vido, Garcia, Lopes and Pereira (2020) | Twenty-eight healthy elderly participants ($M_{age}$ = 66.71 ± 7.64, 24 women) | Baseline HRV was taken followed by a battery of cognitive tests (Wisconsin card sorting task, Stroop, N-back). Then a group of physical ability tests (i.e. timed up and go test). | Neurovisceral integration model[1,3] | Polar HRM V800 heart rate monitor<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, SD1<br><br>**HRV**<br>SDNN, LFnu, HFnu, LF%, HF%, TP, LF/HF, SD2<br><br>(FFT) | vmHRV (RMSSD, SD1) and HRV (HF% and HFnu) were positively correlated with card sorting task performance while HRV (LF and SD2/SD1 ratio) were negatively correlated. |
| de Souza et al. (2020) | Fifty-four university professors ($M_{age}$ = 42.59 ± 9.20) | Participants answered stress questionnaires around stress and physical activity. Participants aerobic capacity was measured via a submaximal test. | N/A | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline), event (exercise) resting (post exercise) recovery, reactivity | **vmHRV**<br>RMSSD, SD1 | For men an increase in stress (higher work control, perceived stress, stress symptoms) resulted in lower vmHRV withdrawal during test (higher RMSSD exe-rest and SD1 exe-rest). However lower perceived stress was also linked to a lower vmHRV withdrawal during the test. Less control of work activities was associated with an increase in vmHRV post-test (higher RMSSD and SD1 rec-exe).<br><br>For women, lower work demands were associated with an increase in vmHRV after exercise (SD1 rec-exe). |
| Dishman et al. (2000) | Ninety-two healthy physically fit adults (52 men $M_{age}$ = 39.7 ± 9.9, 40 women $M_{age}$ = 40.3 ± 12.5) | After screening for physical fitness, participants completed a trait anxiety questionnaire and reported their stress for the past week. A single 5 minute measurement of HRV was taken. | N/A | Polar Electro Oy<br><br>(R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>HF $ms^2$<br><br>**HRV**<br>SDRR, LF $ms^2$ , LF/HF, HFnu, LFnu (reported as HF TF, LF TF), $TFms^2$ | Participants with higher levels of stress from the past week had lower HRV (HFnu [HF TF] ) – this finding was independent of age, gender, trait anxiety and CV fitness. No other results related to HRV. |

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| | | | | | (TF reported as total power in this paper)<br><br>(Natural transform) | |
| Finkenzeller, Müller and Amesberger (2011) | Thirty-four older adults aged 60+ | Control vs intervention group (12 week skiing) compared psycho-physiological reactions (HRV and SC) to mental stress (tests of the Vienna system including: Cognitrone, the determination test, peripheral perception test). | N/A | NeXus-10 device and software Biotrace1<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), resting (post event) | **HRV**<br>HFnu<br><br>(FFT) | Results showed that the skiing intervention did influence aerobic capacity, however this did not lead to changes in resting HRV (HFnu) or stress reactivity (HFnu), nor did this influence cognitive performance. |
| Franks and Boutcher (2003) | Fifteen trained preadolescent males ($M_{age}$ = 10.3 ± 0.4) and fifteen untrained males ($M_{age}$ = 9.5 ± 0.2) | Trained vs. untrained preadolescents had pre-test anxiety (STAI) and cognitive performance (Stroop, Tetris) tested and cardiovascular responses taken (HRV, cardiac contractility, BP, total peripheral resistance, stroke volume). | N/A | Amlab Physiograph (Model 1.7)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (Stroop), resting (post event) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$MFms^2$<br><br>The natural logarithm of the band-passed variance (ms2 ) was then calculated and used as high (0.12– 0.40 Hz) and medium-frequency (0.06–0.11 Hz) measures of heart period varaiblity ( HRV) | Both groups had a significant reduction in vmHRV ($HFms^2$) during the Stroop task, although trained subjects made fewer errors. Trained individuals had a greater decrease in vmHRV ($HFms^2$) reactivity (from baseline to during the Stroop task). |
| Gidlow et al. (2016) | Thirty-eight healthy adults ($M_{age}$ = 40.9 ± 17.6, 65% male) | Determining psychological (mood, cognitive function, restoration experience) and physiological (HRV, salivary cortisol) reactions to walking in three pleasant environments (urban, green and blue). | N/A | eMotion monitor<br><br>(ECG derived R-R interval)<br><br>Resting (baseline pre-walk), resting (post-walk) | **HRV**<br>SDNN, HFuns ccv, LFuns ccv, LF/HF<br><br>CCV= percentage of coefficient of component variance. Used to control for differences in RR interval as a result | Improvements in mood and cortisol were present in all environments and cognitive performance improved in green and blue, however no significant findings were associated to HRV. |

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| | | | | | of different exercise intensities.<br><br>(FFT, log transformed) | |
| von Harren et al. (2016) | Sixty-one inactive students ($M_{age}$ = 21.4 ± 1.8) | Control group vs aerobic exercise training across an academic semester, perceived stress and HRV measured in normal term time (baseline) and real life stress (exam time). | N/A | ecgMove (1 channel ECG)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), resting (post stressor) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>LF/HF<br><br>(FFT) | During real life stress the exercise group showed significantly higher vmHRV (RMSSD) and lower LF/HF than the control. In addition, higher daily activity and perceived stress led to a decrease in vmHRV (RMSSD). |
| Klaperski, von Dawans, Heinrichs and Fuchs (2014) | One hundred and forty-nine healthy males (Exercise group $M_{age}$ = 45.27 ± 1.59, relaxation group $M_{age}$ = 45.08 ± 1.69, control $M_{age}$ = 48.42 ± 2.34) | Participants split between 12 weeks of exercise, relaxation or a waiting list control. Physiological responses to psychological stress (Trier social stress test) assessed pre and post. | N/A | Polar RS800CX<br><br>(R-R interval)<br><br>Resting (baseline), event, resting (post event), reactivity, recovery | **HRV**<br>Relaxation count (RLX) – derived from Polar which is an approximation of SD1<br><br>(Log transformed) | Exercise significantly reduced HRV (RLX) reactivity to the psychological stressor (reduction from T1 to T2), whereas the relaxation condition only reduced cortisol and not RLX. |
| Kuroda, Hudson and Thatcher (2015) | Twenty healthy participants split to ten paratelic ($M_{age}$ = 21.4 ± 6.0, 5 female) and ten telic ($M_{age}$ = 24.3 ± 4.3, 6 female) | State manipulation through video priming (for telic "serious" and paratelic "playful" states) prior to a ramped ergometer test. | Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[4] | ECG (no specified equipment)<br><br>ECG derived R-R interval (HRV Module for Chart v1 for Windows)<br><br>Resting (baseline) | **vmHRV**<br>RMSSD, pNN50, HF $ms^2$<br>**HRV**<br>VLF$ms^2$, LF $ms^2$, LFnu, HFnu, LF/HF, HF%, LF%, LF/HF%<br><br>(FFT) | Motivational dominance can alter psychological and physiological responses to priming before exercise. Telic dominance increased vmHRV (RMSSD, HF$ms^2$) and HRV (HFnu) more than the paratelic dominance group. HRV (LF%) was higher in the telic condition for the telic group, but the opposite was found for the paratelic group. |
| Kubitz and Landers (1993) | Thirty unfit college students ($M_{age}$ = 23.04 ± 3.62) | Physical fitness was measured via $VO_2$ max testing and participants were subjected to mental stress tests (Stroop and mental arithmetic). The experimental group took part in an 8 week aerobic | N/A | Grass Model 12 Neurodata Acquisition System (EEG, EOG and ECG) | **vmHRV**<br>RSA (calculated using spectral power between 0,12 and 0.40 Hz) | Those in the training group had increased vmHRV (RSA) during mental stress, whereas those in the control group (no training) had decreased vmHRV (RSA) during mental stress. |

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| | | training program, and was then retested. | | (ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event) | | |
| Laborde et al. (2019) | 120 university students split between experiment one (60 - $M_{age}$ = 25.57, 25 female) and experiment two (60 - $M_{age}$ = 24.87, 22 female) | Participants performed a physical task (burpees) either with slow-paced breathing (matched with a control), before or after the physical task, influenced inhibition tested via Stroop task. | Vagal tank theory[5], Neurovisceral integration model[1] | eMotion Faros (180°)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), Resting (post exercise, pre Stroop, post Stroop) | **vmHRV**<br>RMSSD | vmHRV (RMSSD) was negatively affected by exercise. Slow-paced breathing did reduce errors in the Stroop task, however this was not mediated by vmHRV (RMSSD). |
| Lin et al. (2018) | Forty-five healthy elderly practitioners ($M_{age}$ = 65.14 ± 9.38, 32 female) | Assessed parameters of physical (i.e. HRV) and psychological state (i.e. anxiety STAI) pre and post one session of Qigong. | N/A | Polar Vantage NV<br><br>(R-R interval)<br><br>Resting (baseline), resting (post event) | **vmHRV**<br>HFms[2]<br><br>**HRV**<br>LFms[2], LFnu and HFnu | Parameters of HRV did not change significantly from pre to post Qigong session. |
| Lin, Huang, Shiu and Yeh (2015) | Sixty mental health professionals split into yoga ($M_{age}$ = 32.07 ± 7.54, male 4) and control ($M_{age}$ = 29.77 ± 6.89, male 8) groups | Stress and HRV measured pre and post a 12 week yoga intervention (1 class of 60 minutes each week) vs control. | N/A | HRV Monitor (V1.89, Yang Ying Inc)<br><br>(R-R/ECG not specified)<br><br>Resting (baseline pre and post intervention) | **HRV**<br>LFuns, HFuns, LF/HF | HRV (LFuns and HFuns) showed no significance between pre and post test, however HRV (LF/HF) was increased in the yoga group. |
| Liu, Cheng, Wang, Lin and Chang (2015) | Forty healthy elementary teachers split into exercise ($M_{age}$ = 43.8 ± 4.5, male 3) and control ($M_{age}$ = 43.0 ± 4.9, male 6) | 12 week walking intervention (walking 3km three times a week), measurements of HRV taken at week 4, 8 and 12 vs control. | N/A | HRV meter (type LR8Z11, one lead ECG)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (during intervention) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>LFuns, HFuns, TP, SDNN<br><br>(FFT) | vmHRV (RMSSD) and HRV (HFuns) and TP were all significantly higher after four weeks of the intervention, after 8 weeks only HRV (RRI) had increased. After 12 weeks of training, vmHRV (RMSSD) and other HRV parameters (HFuns, TP, LFuns, SDNN, and SDSD) were all increased post intervention. |

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| Ludyga, Pühse, Lucchi, Marti and Gerber (2019) | 105 healthy male school children split into moderate intensity exercise ($M_{age}$ = 14.0 ± 0.8), high intensity exercise ($M_{age}$ = 14.0 ± 0.8) and control ($M_{age}$ = 13.9 ± 0.6) | Children participated in either moderate or high intensity exercise intervention (or control). Inhibitory control (Flanker task) was measured prior, immediately after, 30 min after, and 60 min after intervention. | N/A | ecgMove (ECG chest belt)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (during Flanker task), resting (pre exercise, post exercise, 30 min post, 60 min post). | **HRV**<br>LF/HF<br><br>(FFT) | Only moderate intensity exercise reduced reaction times. Greater increases in HRV (LF/HF) were shown after both exercise conditions but not control. No links were found between Flanker performance and HRV (LF/HF). |
| Luft, Takase and Darby (2009) | Thirty track and field athletes ($M_{age}$ = 18.5, range 16-25, 7 female) | Participants completed a baseline CogState test, followed by the battery of tests and an incremental exercise test (Vo2max). Following a 10-15 minute rest the baseline and cognitive tests were repeated. | Neurovisceral integration model[2,3] , Autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone[4] | Nexus-10 system<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>SDNN LF/HF, LF%, HF%, $LFms^2$<br><br>(FFT) | There were no overall effects on cognitive performance pre vs post exercise. There was a significant difference between baseline and cognitive tasks for HRV (SDNN and LF/HF) but not vmHRV (RMSSD). Anticipations were linked to significantly higher HRV (LF%) and lower HRV (HF%). Faster reaction time was correlated to higher LF/HF and slower reaction time were correlated to lower HF%. |
| Luque-Casado, Zabala, Morales, Mateo-March and Sanabria (2013) | Twenty-eight young males split into low fit ($M_{age}$ = 19.5) and high fit ($M_{age}$ = 20.7) | $VO_2$ max tests were first conducted to determine fitness. Following a baseline participants completed three cognitive tasks (Psychomotor vigilance, orientation and discrimination). | Neurovisceral integration model[1,2]– in discussion | FirstBeat Bodyguard monitor<br><br>(R-R interval)<br><br>Continuous measurement of HRV | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN<br><br>(Natural log transform) | The high fit group displayed greater vmHRV (RMSSD) both at baseline and during the tasks. Although the high fit group had higher vmHRV (RMSSD) than the low fit, this did not translate to better executive performance as a whole. |
| Luque-Casado, Perakakis, Ciria and Sanabria (2016) | Forty-four healthy young participants split into low fit ($M_{age}$ = 23) and high fit ($M_{age}$ = 23) | Baseline HRV assessment was completed followed by the psychomotor vigilance task, followed by a submaximal fitness test. | Neurovisceral integration model[1,2] | BioSemi Active Two amplifier system<br><br>(ECG derived R-R interval) | **vmHRV**<br>RMSSD, $HFms^2$ | High-fit showed greater cardiac deceleration in the first blocks, no differences in vmHRV (HF and RMSSD). |

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| | | | | Resting (baseline), event (during cognitive task) | | |
| Matsuo, Matsubara, Shiga and Yamanaka (2015) | Forty-three healthy participants (28 women, $M_{age} = 21.0 \pm 1.2$ and 15 men, $M_{age} = 20.7 \pm 1.7$) | Participants were assessed in pre, during (steady state) and post exercise. At different time points a feeling scale, RPE, self- efficacy and HRV were measured. | N/A | BSM-2401 ECG monitor<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, resting (post event) | **HRV**<br>HFnu and LF/HF | HRV (HFnu) was significantly larger in post exercise than in pre and HRV (LF/HF) was significantly smaller in post than pre. Post exercise self-efficacy was negatively correlated to HRV (HFnu). |
| Meier and Welch (2016) | Thirty-two stressed university students ($M_{age} = 21.7 \pm 3.1$, 11 male) | Within-subject design of three interventions (walking, slow-paced breathing with biofeedback and quiet study), for each intervention pre and post measures of HRV, state anxiety and affect. | N/A | Nexus 10 hardware and Biotrace<br><br>(ECG derived R-R interval)<br><br>Resting (baseline pre and post intervention) | **vmHRV**<br>RMSSD<br><br>**HRV**<br>SDNN | State anxiety was significantly reduced by slow-paced breathing with biofeedback only. In all three conditions HRV (SDNN) was increased, no findings related to vmHRV (RMSSD). HRV (SDNN) was negatively correlated with energy in the slow-paced breathing with biofeedback condition and vmHRV (RMSSD) was increased after exercise and positively correlated to tiredness and tension. |
| Murray and Russoniello (2012) | One hundred and twenty participants (60 female, $M_{age} = 21.05 \pm 2.87$, 60 male, $M_{age} = 20.67 \pm 2.80$) | Participants were split into four groups (active exercise, non-active exercise, active control, non-active control) and had HRV measured and cognitive function tested pre and post exercise. | Neurovisceral integration model[2] | Biocom pulse wave sensor M-2001<br><br>(PPG derived R-R interval)<br><br>Resting (baseline pre and post testing) | **HRV**<br>VLFuns, LFuns, HFuns, LFnu, HFnu, LF/HF, TP | Only the exercise groups showed a trend in HRV (LFnu) and post trail-making task which followed an inverted U, meaning those with moderate HRV (LFnu - named arousal in this study) performed better on the task. |
| Nakajima, Chen and Flemming (2017) | Seventy-four healthy college students (experimental $M_{age} = 20.46 \pm 3.05$, 95 % female, control $M_{age} = 19.67 \pm 1.51$, 72% female) | Participants were split into a residual arousal and no residual arousal group. After a resting HRV measure, participants watched two videos (negative emotions and positive emotions). In the residual arousal group, participants completed a | N/A | Biopac MP35<br><br>(ECG derrvied R-R interval)<br><br>Resting (baseline), event (positive and negative video) | **HRV**<br>LFuns and HFuns (AR and FFT) – LF/HF<br><br>(Natural log transform) | In both the residual arousal group and no residual arousal group HRV (LF/HF) was lower during the negative video than the positive video. |

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| | | 1 min vigorous cycle before the video. | | | | |
| Oliveira, Araújo and Abreu (2014) | Sixty participants actively taking part in physical activity ($M_{age}$ = 21.55 ± 2.41, 30 female) | Participants viewed a motor or non-motor movie. Cognitive, motor and proneness to exercise tests were measured pre and post movie viewing. Psychophysiological variables (including HRV) was measured throughout. | N/A | Polar RS800<br><br>(R-R interval)<br><br>Resting (baseline), event (videos) | **HRV**<br>HRSD (the variability associated to the number of beats, heart rate standard deviation), SDNN | After the non-motor movie HRV (SDNN) decreased. HRV (HRSD) was significantly reduced in the non-motor group (from part 1 to part 2 of the movie), this then increased from 2-3, which was linked to mental effort. |
| Oliver, Morton, Baldwin and Datta (2020) | Sixty-seven healthy adults ($M_{age}$ = 20.86 ± 4.23, 41 female) | Participants completed the perceived wellness survey prior to a five minute resting baseline (HRV, HR and skin conductance). Followed by four fitness tests (body composition, cardiorespiratory fitness, muscular fitness and flexibility). | N/A | Procomp InfinitiTM and Biograph software system<br><br>(ECG derived R-R interval)<br><br>Resting (baseline) | **HRV**<br>VLF%, LF%, HF%, LF/HF, SDNN | Although physical markers of fitness were shown to be linked to perceived wellness, no significant correlations were found between HRV parameters and perceived wellness. |
| Sakuragi and Sugiyama (2006) | Fifteen healthy female college students (Experimental group $M_{age}$ = 19.4 ± 1.4, control group $M_{age}$ = 20.1 ± 1.2) | Medical screening, mood (POMS), physiological data (EEG,ECG,BP) and response to a video game were taken pre and post a four week walking intervention. | N/A | ECG system (not named)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event,<br>Reactivity | **HRV**<br>LFms, HFms, LF/HF<br><br>(ms measure = the amplitude of each frequency band was obtained as twice the power magnitude and the square root thereof) | HRV (LF/HF) reactivity increased significantly when completing the video game task after the walking period. Amount of exercise was shown to be a significant contributor to resting HRV (HFms), but no relationship was found between HRV parameters and POMS subscales. |

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| Sangachin, Gustafason and Cavutoto (2016) | Thirty healthy participants ($M_{age}$ = 23.2 ± 3.1) | Within-subject design testing three workstation types (sitting, standing and walking). Participants completed a mouse, keyboard and cognitive task. | N/A | RS800CX, Polar Electro Inc<br><br>(R-R interval)<br><br>Resting (between each trial) | **vmHRV**<br>RMSSD | vmHRV (RMSSD) significantly reduced depending on the workstation type with sitting having the highest and standing the lowest. vmHRV (RMSSD) was not correlated to subjective mental workload. |
| Schinkoeth, Weymar and Brand (2019) | Ninety-one young adults ($M_{age}$ = 23.4 ± 5.9, 50 female) | Participants rated their habitual exercise. Then viewed neutral and exercise images whilst HRV was recorded, following the presentation of images, valence and arousal were measured (via the Self-assessment manikin). | Neurovisceral integration model[3] | Polar RS800 and RS800CX<br><br>(R-R interval)<br><br>Resting (baseline), event | **vmHRV**<br>RMSSD<br><br>(Natural log transform) | Higher levels of exercise led to greater vmHRV (RMSSD). Those who exercised less had lower vmHRV (RMSSD) when viewing the images and reported low affective valence and arousal. vmHRV (RMSSD) and affective states were not linked. |
| Sloan et al. (2011) | One hundred and forty-nine healthy untrained individuals (72 aerobic training $M_{age}$ = 30.0 ± 0.83, strength training $M_{age}$ = 31.29 ± 0.92) | 12-week exercise intervention (aerobic or strength training). Reaction to psychological stress (HRV) was measured during a Stroop, public speaking task and maths task – assessed pre, post and 4 weeks post. | N/A | National Instruments 16 bit A/D conversion board<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event (stressor), resting (post event) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>SDNN, $LFms^2$<br><br>(Log transformed) | All HRV indices fell as a response to the mental challenges and increased in recovery. vmHRV (RMSSD) rose from baseline to post training as a result of aerobic training but not strength training. However, there was no effect on reactivity and recovery from mental stress on HRV for either training condition. |
| Spalding, Jeffers, Porges and Hatfeild (2000) | Twenty male participants (Ten trained $M_{age}$ = 23.8 ± 0.6) and ten untrained $M_{age}$ = 22.2 ± 0.8) | Testing consisted of two days, one involving a test of aerobic capacity and the second involving a stress test (three psychological tests included mental arithmetic, general knowledge and Stroop task). | N/A | Transkinetics, Model TXM-205 (ECG transmitter)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline), event, reactivity, recovery | **vmHRV**<br>RSA (via Porges method [Porges, 1985])<br><br>(Natural log transform) | No significant differences in vmHRV (RSA) at rest between trained and untrained. Phasic changes to stress and recovery were not significantly different. Aerobic capacity ($VO_2$ max) was not related to vmHRV (RSA) levels or phasic changes during stress and recovery. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Tang et al. (2020) | 55 healthy older adults ($M_{age}$ = 64.38 ± 13.95, 17 male) | For a 10-year period participants either completed mindfulness meditation or physical exercise (walking). Multiple physiological measures were taken (HRV, salivary cortisol, EEG, skin conductance) and a quality of life survey. | N/A | Procomp Infiniti System from Thought Technology<br><br>(ECG derived R-R interval)<br><br>Resting (baseline) (multiple points) | **HRV**<br>HFnu% | HRV (HFnu%) was higher in the mindfulness group when compared to the physical activity group (the same pattern was found in skin conductance). |
| Wadden et al. (2018) | Thirty-one participants (19 yoga practitioners $M_{age}$ = 35.89 ± 11.59, 12 recreational athletes $M_{age}$ 32.58 ± 9.13) | Participants were screened with a battery of questionnaires (i.e. relaxation, stress, mindfulness). They then completed an emotion-eliciting task (video clips) whilst having fMRI and HRV measured. | Neurovisceral integration model[3] | Philips Achieva 3.0 T whole-body MR scanner<br><br>(ECG derived R-R interval)<br><br>Event | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$LFms^2$, LF/HF<br><br>(AR) | Overall the groups did not differ in vmHRV ($HFms^2$). HRV (LF/HF) was lower in the yoga group than in the recreational athlete group during the emotion related stimuli. No significant relationships between HRV and brain activity. |
| Weinstein, Deuster and Kop (2007) | Forty healthy participants actively involved in exercise (Control $M_{age}$ = 32.6 ± 7.8, Withdrawal $M_{age}$ = 30 ± 7.2) | Participants were randomly assigned to either stop (withdrawal) or continue (control) aerobic exercise. Baseline measures were taken (HRV, mood, fatigue, activity levels) and repeated after two weeks. | N/A | Three-lead ECG monitor (Marquette Medical Systems Series 8500)<br><br>(ECG derived R-R interval)<br><br>Resting (baseline) | **vmHRV**<br>$HFms^2$<br><br>**HRV**<br>$LFms^2$ , LF/HF<br><br>(Log transform)<br><br>(FFT) | HRV (LF/HF) was positively correlated with higher levels of the fatigue index in the exercise withdrawal group. In this group there was also a trend towards a positive relationship between HRV (LF/HF) and negative mood. Nonetheless, there were no significant changes in baseline vmHRV ($HFms^2$) or HRV ($LFms^2$ , $HFms^2$, LF/HF) over the two weeks. |
| Zaffalon, Viana, de Melo and Angelis (2018) | Ninety-six participants (Active $M_{age}$ = 23.3 ± 3.7, Sedentary $M_{age}$ = 23.1 ± 3.9) | Participants had HRV baseline measured followed by a mental stress test (Stroop task), after which recovery HRV was measured. | N/A | Polar® V800<br><br>(R-R interval)<br><br>Resting (baseline), resting (post event) | **vmHRV**<br>RMSSD, $HFms^2$<br><br>**HRV**<br>LFnu, HFnu, $LFms^2$, LF/HF<br><br>(FFT) | Significant differences at rest between active and sedentary women were found between vmHRV (RMSSD and $HFms^2$), and HRV (HFnu and LFnu). In both recovery phases (2-5 min, 6-9 min) all HRV parameters were significantly different between groups with the exception of HRV ($LFms^2$). More specifically – vmHRV (RMSSD, $HFms^2$ ) and HRV (HFnu) were higher and HRV (LFnu and LF/HF) were decreased in active women. |
| Zheng et al. (2018) | Sixty-nine healthy but stressed participants ($M_{age}$ = 33.9, 11 male) | Participants were randomly assigned to a Thai chi, exercise or waiting list control group. | N/A | Flexcomp Infinity<br><br>(ECG derived R-R interval) | **vmHRV**<br>$HFms^2$<br><br>**HRV** | All vmHRV and HRV parameters showed no changes across the three groups at any time point. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | They then took part in a 12-week intervention with pre, mid and post testing (including HRV and anxiety scores). | | Resting (baseline) | $VLFms^2$, $LFms^2$, $TPms^2$, LF/HF, LFnu, HFnu | |

Theory references

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[3]Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders, 61*, 201-216. https://doi.org/10.1016/S0165-0327(00)00338-4

[4]Friedman, B.H. (2007). An autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone. *Biological Psychology, 74*, 185-199.

[5]Laborde, S., Mosley, E., & Mertgen, A. (2018). Vagal Tank Theory: The Three Rs of Cardiac Vagal Control Functioning - Resting, Reactivity, and Recovery. *Frontiers in Neuroscience, 12*, 458. https://doi.org/10.3389/fnins.2018.00458

Table 5: Quality Appraisal using the Mixed Methods Appraisal Tool (Hong et al., 2018).

| **Quantitative randomized control trials** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Study** | **S1** | **S2** | **2.1** | **2.2** | **2.3** | **2.4** | **2.5** |
| Albinet (2010) | Y | Y | N | Y | Y | N | Y |
| Albinet (2016) | Y | Y | N | Y | Y | N | Y |
| Albracht-Schulte (2018) | Y | Y | Y | Y | Y | N | N |
| Cheema (2013) | Y | Y | Y | Y | N | CT | Y |
| De Gues (1990) | Y | Y | N | N | Y | N | Y |
| Dziembowska (2016) | Y | Y | N | Y | Y | N | CT |
| von Haaren (2016) | Y | Y | N | Y | N | N | CT |
| Hunt (2018) | Y | Y | N | N | Y | N | Y |
| Klaperski (2014) | Y | Y | N | Y | N | N | Y |
| Lin (2015) | Y | Y | Y | Y | N | Y | Y |
| Murray (2012) | Y | Y | N | CT | Y | N | Y |
| Patil (2013) | Y | Y | Y | Y | Y | N | N |
| Paul and Garg (2012) | Y | Y | N | Y | Y | Y | Y |
| Paul (2012) | Y | Y | N | CT | Y | Y | Y |
| Penna (2018) | Y | Y | CT | Y | Y | N | N/A |
| Rollo (2017) | Y | Y | N | N | N | N | Y |
| Rusciano (2017) | Y | Y | N | Y | Y | N | Y |
| Sakuragi (2006) | Y | Y | N | Y | Y | N | Y |
| Sloan (2011) | Y | Y | N | Y | Y | N | N |
| Weinstein (2007) | Y | Y | N | Y | Y | N | Y |
| Zheng (2018) | Y | Y | Y | Y | Y | Y | N |
| **Questions** | S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?<br><br>2.1. Is randomization appropriately performed? 2.2. Are the groups comparable at baseline? 2.3. Are there complete outcome data? 2.4. Are outcome assessors blinded to the intervention provided? 2.5 Did the participants adhere to the assigned intervention? | | | | | | |
| **Quantitative non-randomized** | | | | | | | |
| **Study** | **S1** | **S2** | **3.1** | **3.2** | **3.3** | **3.4** | **3.5** |
| Alderman (2014) | Y | Y | Y | Y | Y | Y | Y |
| Ayuso-Moreno (2020) | Y | Y | Y | Y | Y | N | Y |
| Barreto-Silva (2018) | Y | Y | Y | Y | Y | N | Y |
| Benzing (2016) | Y | Y | Y | Y | N | Y | Y |
| Bisschoff (2016) | Y | Y | Y | Y | Y | N | Y |
| Boutcher (1998) | Y | Y | Y | Y | Y | N | Y |
| Botonis (2021) | Y | Y | Y | Y | Y | N | Y |
| Britton (2019) | Y | Y | Y | Y | Y | Y | Y |
| Ceccarelli (2019) | Y | Y | Y | Y | Y | Y | Y |
| Cervantes Blásquez (2009) | Y | Y | Y | Y | Y | N | Y |
| Choudhary (2016) | Y | Y | Y | Y | Y | N | Y |
| Crawford (2019) | Y | Y | Y | Y | Y | Y | Y |
| D'Ascenzi (2014) | Y | Y | Y | Y | Y | N | Y |
| da Silva (2017) | Y | Y | Y | Y | Y | N | Y |
| da Silva (2020) | Y | Y | Y | Y | Y | Y | Y |
| De Oliveria Matos (2020) | Y | Y | Y | Y | Y | N | Y |
| De Souza (2020) | Y | Y | Y | Y | Y | Y | Y |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dishman (2000) | Y | Y | Y | Y | Y | Y | Y |
| Dobson (2020) | Y | Y | Y | Y | Y | Y | Y |
| Dupuy (2014) | Y | Y | Y | Y | Y | Y | Y |
| Dupuy (2018) | Y | Y | Y | Y | Y | Y | Y |
| Finkenzeller (2011) | Y | Y | Y | Y | N | N | Y |
| Flat (2018) | Y | Y | Y | Y | Y | N | Y |
| Fortes (2017) | Y | Y | Y | Y | Y | N | Y |
| Franks (2003) | Y | Y | Y | Y | Y | N | Y |
| Frenkel (2019) | Y | Y | Y | Y | Y | Y | Y |
| Gantois (2019) | Y | Y | Y | Y | Y | N | Y |
| Gidlow (2016) | Y | Y | Y | Y | Y | N | Y |
| Hauer (2020) | Y | Y | Y | Y | Y | N | Y |
| Holguín-Ramírez (2020) | Y | Y | Y | Y | Y | N | Y |
| Huang (2018) | Y | Y | Y | Y | Y | Y | Y |
| Hutchison (2016) | Y | Y | Y | Y | Y | Y | Y |
| Hynynen (2008) | Y | Y | Y | Y | Y | Y | Y |
| Iellamo (2003) | Y | Y | Y | Y | Y | N | Y |
| Kim (2019) | Y | Y | Y | N | Y | Y | Y |
| Korobeynikov (2011) | Y | Y | Y | N | Y | N | Y |
| Kubitz (1993) | Y | Y | Y | Y | Y | N | Y |
| Kuroda (2015) | Y | Y | Y | Y | Y | N | Y |
| Laborde (2011) | Y | Y | Y | Y | Y | N | Y |
| Laborde (2015) | Y | Y | Y | Y | Y | Y | Y |
| Laborde (2019) | Y | Y | Y | Y | Y | Y | Y |
| Landolt (2017) | Y | Y | Y | Y | Y | N | Y |
| Lin (2018) | Y | Y | Y | Y | Y | N | Y |
| Liu (2015) | Y | Y | Y | Y | Y | N | Y |
| Loizou (2015) | Y | Y | Y | Y | Y | Y | Y |
| Ludyga (2019) | Y | Y | Y | Y | Y | Y | Y |
| Luft (2009) | Y | Y | Y | Y | Y | N | Y |
| Luque-Casado (2013) | Y | Y | Y | Y | Y | N | Y |
| Luque-Casado (2016) | Y | Y | Y | Y | Y | N | Y |
| Mamlouk (2021) | Y | Y | Y | Y | Y | N | Y |
| Mateo (2012) | Y | Y | Y | Y | Y | Y | Y |
| Matsuo (2015) | Y | Y | Y | Y | Y | Y | Y |
| Matylda (2021) | Y | Y | Y | Y | Y | Y | Y |
| Meier (2016) | Y | Y | Y | Y | N | N | Y |
| Móra (2022) | Y | Y | Y | Y | Y | N | Y |
| Morales (2012) | Y | Y | Y | Y | Y | Y | Y |
| Morales (2019) | Y | Y | Y | Y | Y | N | Y |
| Mosley (2017) | Y | Y | Y | Y | Y | Y | Y |
| Mosley (2018a) | Y | Y | Y | Y | Y | Y | Y |
| Mosley (2018b) | Y | Y | Y | Y | Y | Y | Y |
| Nakajima (2017) | Y | Y | Y | Y | Y | Y | Y |
| Nicolas (2019) | Y | Y | N | Y | Y | N | Y |
| Oliveira (2014) | Y | Y | Y | Y | Y | N | Y |
| Oliveira-Silva (2018) | Y | Y | Y | Y | Y | N | Y |
| Ortega (2018a) | Y | Y | Y | Y | Y | N | Y |
| Ortega (2018b) | Y | Y | Y | Y | Y | Y | Y |
| Ortigosa-Martinez (2017) | Y | Y | Y | Y | Y | N | Y |
| Park (2020) | Y | Y | Y | Y | Y | N | Y |
| Parrado (2013) | Y | Y | Y | Y | Y | N | Y |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Perkins (2010) | Y | Y | Y | Y | Y | N | Y |
| Perry (2019) | Y | Y | Y | N | Y | N | Y |
| Piatrikova (2021) | Y | Y | Y | Y | Y | N | Y |
| Portillo (2020) | Y | Y | Y | Y | Y | Y | Y |
| Sangachin (2016) | Y | Y | Y | Y | Y | Y | Y |
| Schinkoeth (2019) | Y | Y | Y | Y | Y | Y | Y |
| Sartor (2013) | Y | Y | Y | Y | N | N | Y |
| Sartor (2016) | Y | Y | Y | Y | Y | N | Y |
| Shaw (2012) | Y | Y | Y | Y | Y | N | Y |
| Souza (2019) | Y | Y | Y | Y | Y | N | Y |
| Spalding (1999) | Y | Y | Y | Y | Y | N | Y |
| Tang (2020) | Y | Y | Y | Y | Y | Y | Y |
| Thornton (2019) | Y | Y | Y | Y | Y | N | Y |
| Vacher (2018) | Y | Y | Y | Y | Y | Y | Y |
| Vacher (2019) | Y | Y | Y | Y | Y | Y | Y |
| Vaz (2019) | Y | Y | Y | Y | Y | N | Y |
| Wadden (2018) | Y | Y | Y | Y | Y | Y | Y |
| Yen (2012) | Y | Y | Y | Y | Y | Y | Y |
| You (2020) | Y | Y | Y | Y | Y | Y | Y |
| You (2021) | Y | Y | Y | Y | Y | Y | Y |
| Zaffalon (2018) | Y | Y | Y | Y | Y | N | Y |
| **Questions** | S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?<br><br>3.1. Are the participants representative of the target population? 3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)? 3.3. Are there complete outcome data? 3.4. Are the confounders accounted for in the design and analysis? 3.5. During the study period, is the intervention administered (or exposure occurred) as intended? | | | | | | |
| **Quantitative descriptive** | | | | | | | |
| **Study** | **S1** | **S2** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** |
| Daly (2014) | Y | Y | Y | Y | Y | Y | Y |
| Lagos (2008) | Y | Y | Y | Y | Y | Y | Y |
| Neumann (2009) | Y | Y | Y | Y | Y | Y | Y |
| Oliver (2020) | Y | Y | Y | Y | Y | Y | Y |
| Paula (2016) | Y | Y | Y | Y | N | Y | N |
| Tibana (2019) | Y | Y | Y | Y | Y | Y | Y |
| **Questions** | S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?<br><br>4.1. Is the sampling strategy relevant to address the research question? 4.2. Is the sample representative of the target population? 4.3. Are the measurements appropriate? 4.4. Is the risk of nonresponse bias low? 4.5. Is the statistical analysis appropriate to answer the research question? | | | | | | |
| **Mixed methods** | | | | | | | |
| **Study** | **S1** | **S2** | **5.1** | **5.2** | **5.3** | **5.4** | **5.5** |
| Gross (2017) | Y | Y | Y | Y | Y | Y | N |
| **Questions** | S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?<br><br>5.1. Is there an adequate rationale for using a mixed methods design to address the research question? 5.2. Are the different components of the study effectively integrated to answer the research question? 5.3. Are the outputs of the integration of qualitative and quantitative components adequately interpreted? 5.4. Are divergences and inconsistencies between quantitative and qualitative results adequately addressed? 5.5. Do the different components of the study adhere to the quality criteria of each tradition of the methods involved? | | | | | | |

[a] Y = Yes, N = No, CT = Can't Tell, N/A = Not Applicable.
[b] Studies displayed belong to both sport psychology and exercise psychology and identified with the first author only.
[c] Studies have been separated out into each individual study design, due to the differentiation in questions. There were no studies that used a qualitative research design.
[d] These questions were answered in relation to all study elements and not just HRV. For specific HRV measurement and interpretation critiques, please see the discussion.

Table 6: Benchmarks for SEP researchers and practitioners using HRV

| *SEP use* | *Parameters to consider* | *Guidance* |
|---|---|---|
| *Cognitive performance* | vmHRV (RMSSD, HF $ms^2$) | Based on the neurovisceral integration model (Thayer et al., 2009), vmHRV is suggested to be related specifically to executive performance, e.g., decision making, working memory |
| *Emotion regulation* | vmHRV (RMSSD, HF $ms^2$) | Rather than a physiological marker of specific emotions, e.g., anxiety, vmHRV may be used to investigate emotion regulation, based on the neurovisceral integration model (Thayer et al., 2009) |
| *Injury* | vmHRV (RMSSD, HF $ms^2$) | Due to its links with inflammatory processes (Williams et al., 2019), vmHRV may be used in conjunction with subjective parameters of injury experience and recovery |
| *Overtraining/ burnout / recovery* | vmHRV (RMSSD, HF $ms^2$) | Due to evidence surrounding HRV as a marker of overtraining (Bosquet et al., 2008) vmHRV may be used in conjunction with subjective parameters of overtraining, burnout, and recovery, e.g., REST-Q |
| *Pain* | vmHRV (RMSSD, HF $ms^2$) | Due to links between pain and vmHRV (Koenig et al., 2014) vmHRV may be used in conjunction with experimentally induced pain and subjective parameters of pain, e.g., subjective pain ratings |
| *Performance* | vmHRV (RMSSD, HF $ms^2$) | Due to its links with self-regulatory processes (Thayer et al., 2009), vmHRV may be assessed together with performance, in case performance is expected to rely mostly on cardiac vagal activity |
| *Pre-competitive anxiety* | See stress | See stress |
| *Slow-paced breathing with / without HRV Biofeedback* | vmHRV (RMSSD, HF $ms^2$, LF $ms^{2*}$) | Due to the stimulation of the vagus nerve during slow-paced breathing (Gerritsen & Band, 2018; Noble & Hochman, 2019; Sevoz-Couche & Laborde, 2022) investigating vmHRV during and after slow-paced breathing (with/without biofeedback) may help to understand to which extent the vagus nerve is stimulated. Additionally, it can help to determine the resonance frequency (Shaffer & Meehan, 2020). Note: During slow-paced breathing, in the frequency-domain cardiac vagal activity was found to switch from HF$ms^2$ to LF$ms^2$ (Kromenacker et al., 2018) |
| *Self-Control* | vmHRV (RMSSD, HF $ms^2$) | Due to its links with self-regulatory processes (Thayer et al., 2009), vmHRV may be measured alongside tasks involving self-control |
| *Sleep* | vmHRV (RMSSD, HF $ms^2$) | Given the role of the vmHRV in both clinical sleep applications (Stein & Pu, 2012) and healthy populations (Laborde et al., 2019), |

| | | |
|---|---|---|
| | | vmHRV can be measured overnight and upon waking. |
| *Stress* | vmHRV (RMSSD, HF $ms^2$) in conjunction with other stress biomarkers, such as the pre-ejection period and cortisol for example | Investigating the stress response requires measuring the activity of the two branches of the autonomic nervous system (i.e., sympathetic and parasympathetic), as well as the activity of the hypothalamo-pituitary-adrenal (HPA) axis. (Cardiac) sympathetic nervous activity can be indexed via the pre-ejection period, cardiac vagal activity with vmHRV, and the activity of the HPA axis with cortisol. Additionally, subjective self-report indicators of perceived stress may be considered. |

*Note:* It should be noted here for the frequency-domain, that $HFms^2$ is suggested to reflect vmHRV when breathing frequency is comprised between 9 and 24 cpm (Berntson et al., 1997; Laborde et al., 2017; Malik, 1996) which usually encompasses the range of spontaneous breathing (Tortora, 2014), though for athletes spontaneous breathing can also be lower (Saboul et al., 2014). Consequently, for a proper interpretation of $HFms^2$, it is suggested to systematically assess the respiratory frequency.

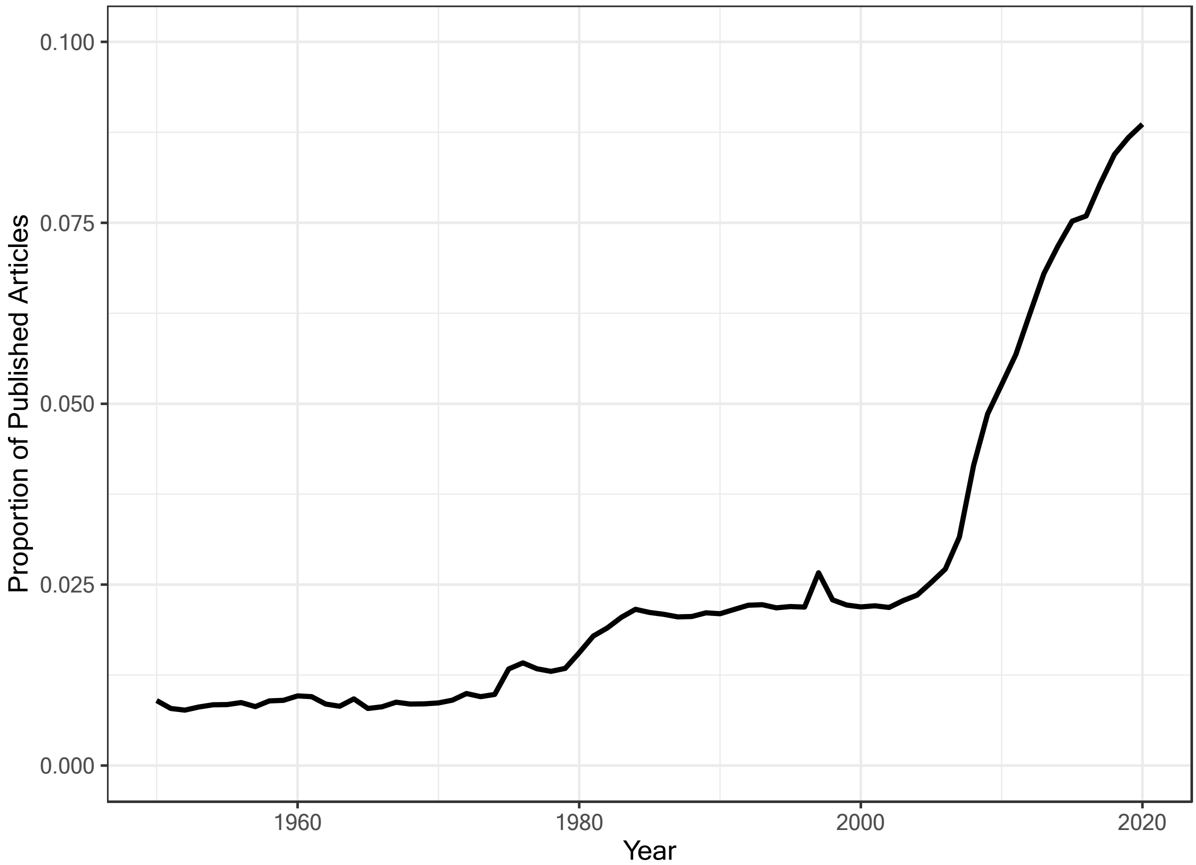


Figure 1: Number of articles using the words “Heart rate variability” OR “HRV” OR “Parasympathetic” OR “Vagal” OR “Vagus” AND “Sport” OR “Exercise” OR “Physical activity” as a proportion of all articles in Europe PubMed Central (PMC) (using the “europepmc” package in R - https://cran.rproject.org/web/packages/europepmc/europepmc.pdf).

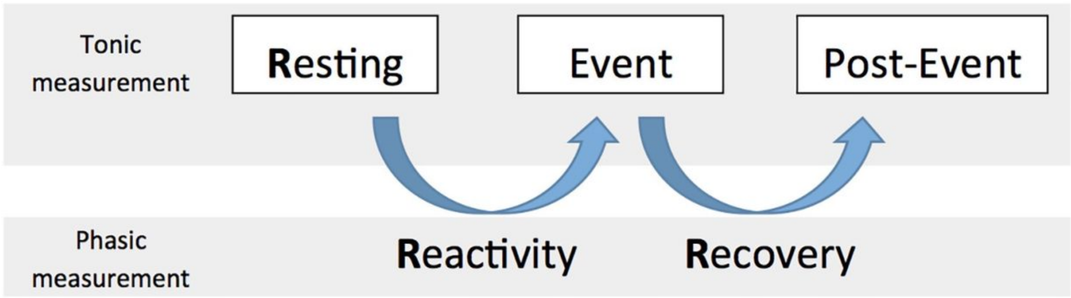


Figure 2: Visual display of measurement times (Taken from Laborde et al., 2018, p.6)

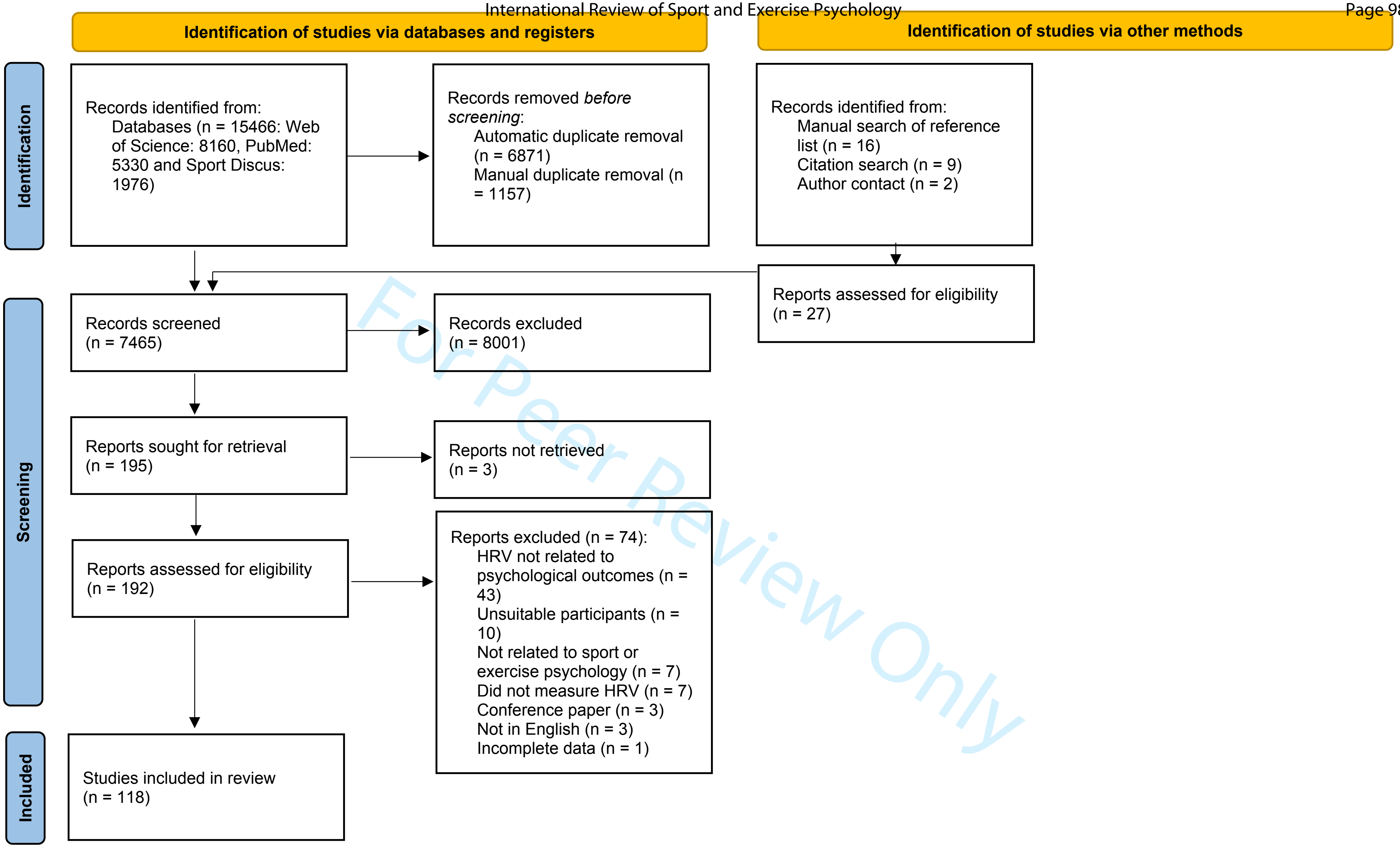




Figure 3: PRISMA flow diagram (Adapted from Page et al., 2021)
*adapted to fit the new version of the flow diagram as the initial search began prior to publication of the new guidelines.

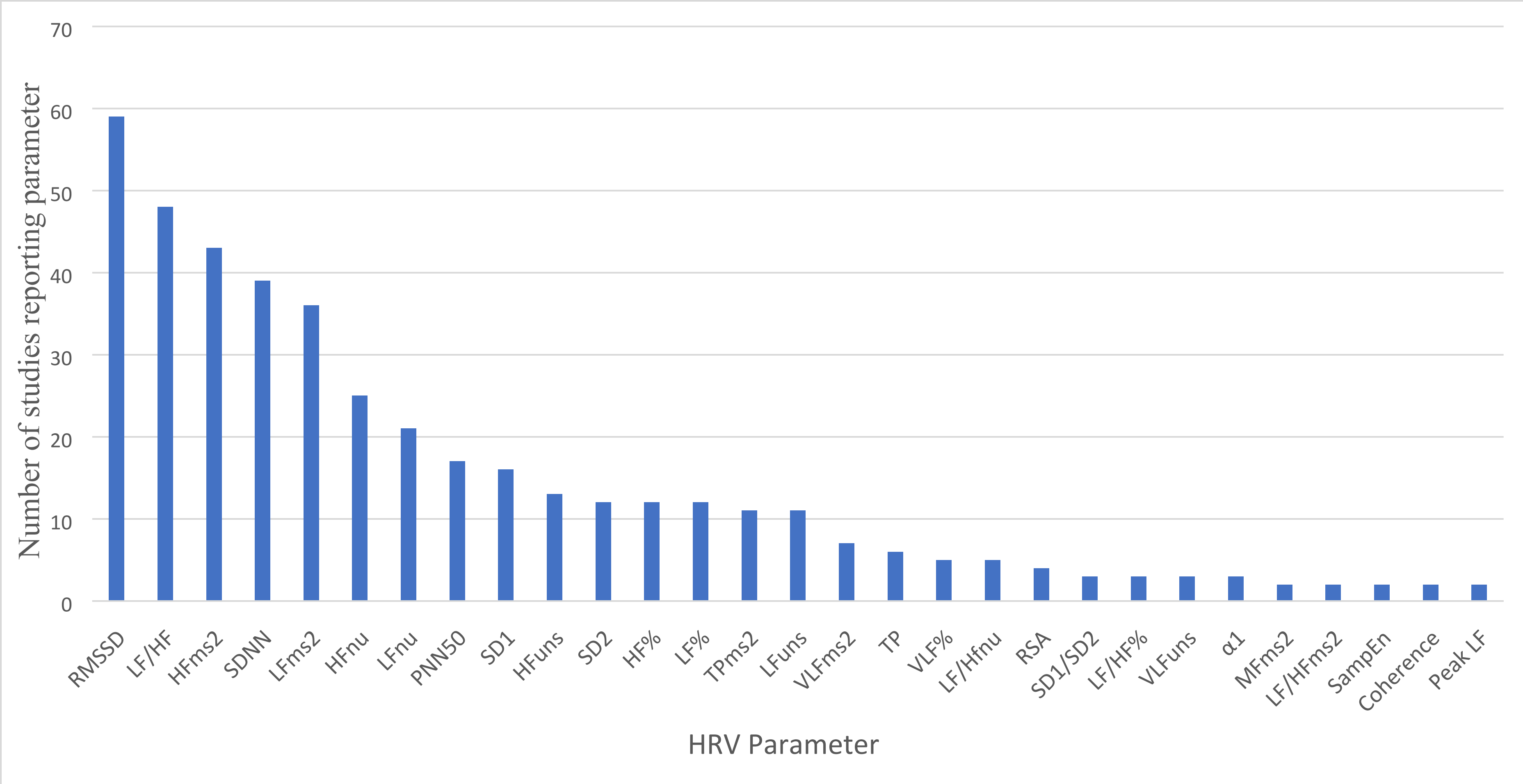


Figure 4: Frequency of HRV parameters reported (for variable explanations please see Supplementary Material 2c)
*Note: the following parameters were only reported once and therefore omitted from the graph – α2, peak VLF, peak HF, NN50nu, RMSSD index, LF+HF, stress index, HFnu%, HF/(LF+HF)nu, LFuns ccv, HFuns ccv, HRSD, LFms, HFms, RLX.

(In order of the graph : RMSSD = root mean square of successive differences; LF/HF = low frequencies / high-frequencies ratio; $HFms^2$ = absolute power of high frequencies; SDNN = standard deviation of all R-R intervals; $LFms^2$ = absolute power of low frequencies; HFnu = normalised units of high frequencies; LFnu = normalised units of low frequencies; PNN50 = percentage of successive normal sinus RR intervals more than 50ms; SD1 = standard deviation - poincaré plot crosswise ; HFuns = high frequency units not specified; SD2 = standard deviation - poincaré plot lengthwise; HF% = percentage power of high frequencies; LF% = percentage power of low frequencies; $TPms^2$ = total power of frequency domain in 24 hours absolute power; LFuns = low frequency unit not specified; $VLFms^2$ = very-low frequencies absolute power; TP = total power; VLF% = percentage of very-low frequencies; LF/HFnu = low frequency/high frequency ratio normalised units; RSA = respiratory sinus arrhythmia; SD1/SD2 = ratio of SD1 and SD2; LF/HF% = percentage of low frequency/high frequency ratio; VLFuns = very-low frequencies units not specified; α1 = detrended fluctuation analysis (short term); $MFms^2$ = absolute power of medium frequencies; $LF/HFms^2$ = absolute power of low frequency/high frequency ratio; SampEn = sample entropy; Coherence = percentage of time spent in each frequency domain; Peak LF = low frequency peak percentage of TP; α2 = detrended fluctuation analysis (long term); Peak VLF = very-low frequency peak percentage of TP; Peak HF = high frequency peak percentage of TP; NN50nu = number of interval differences of successive NN intervals more than 50 ms; RMSSD index = presented as a number between 1-100 from the ithlete™ device; LF+HF = low frequency + high frequency; stress index = is the result of square root of Baevsky's stress index; HFnu% = percentage of change in normalized units of high-frequency; HF/(LF+HF)nu = high frequency divided by LF+HF; LFuns ccv = percentage of coefficient of component variance; HFuns ccv = percentage of coefficient of component variance; HRSD = the variability associated to the number of beats, heart rate standard deviation; LFms = the amplitude of the low frequency band was obtained as twice the power magnitude and the square root thereof; HFms = the amplitude of high frequency band was obtained as twice the power magnitude and the square root thereof; RLX = derived from Polar which is an approximation of SD1)