Effect of an eight-week smartphone-guided HRV-biofeedback intervention on autonomic function and impulsivity in healthy controls

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Abstract
A large body of scientific studies suggest a close relationship between increased vagal function and better cognitive performance. Objective: In the current study, we investigated the association between autonomic function and behavioral impulsivity. We hypothesized that heart rate variability (HRV) biofeedback training increases HRV and enhances inhibitory control. Approach: A total of 28 healthy participants were recruited. After drop-out, 14 participants completed an eight-week HRV biofeedback training with five training sessions per week including one session at the clinic’s laboratory and four sessions at home using a mobile application running on their smartphone. Ten control subjects matched with respect to age and gender played a mobile game according to the same schedule as the biofeedback group. The assessment of autonomic status and the stop-signal task were conducted before the beginning of the training (T1) and after finishing the schedule (T2). Main results: We found a relationship of reaction times in the stop-signal task and standard HRV as well as cardiorespiratory indices. After biofeedback training, short-term HRV and baroreflex function significantly increased by 33% (CI [2%, 64%], \( p < 0.05 \)) and 21% (CI [5%, 36%], \( p < 0.05 \)), respectively. The performance in the stop-signal task was not affected by the biofeedback intervention. Compared to the changes of autonomic indices in the control group, only a decrease of skin conductance levels in the biofeedback group remained statistically significant. Significance: Our results indicate that a smartphone-based HRV biofeedback intervention can be applied to improve cardiovagal function in healthy subjects. Although higher HRV was associated with higher levels of inhibitory control, HRV biofeedback had no effect on measures of impulsivity.

Introduction
Perceptions, cognitions and emotions interact with autonomic nervous control in specific ways and at various levels of the neuraxis. In recent years, parasympathetic cardiac activity has been suggested to index efficient allocation of attentional and cognitive resources needed for competent functioning in a challenging environment (Thayer et al 2009).

High heart rate variability (HRV) is a marker of vagal modulation that has been associated with optimal executive functioning in younger adults (Hansen et al 2003, Sutterlin et al 2011) and older populations (Mathewson et al 2011). Conversely, some studies suggest that cognitive processing, especially executive functions, might be impaired in conditions with reduced autonomic regulatory capacity such as cardiovascular disease or hypertension (Robbins et al 2005). Furthermore, previous studies have indicated that people with higher resting HRV exhibit effective behavioral responses (e.g. faster response times and better accuracy) on cognitive tasks tapping...
executive functions as well as flexible and adaptive emotional responses (Hansen et al 2003, Ruiz-Padial et al 2003). Thus, resting HRV is indicative of self-regulatory abilities. The higher an individual’s HRV the better the performance in tasks requiring response inhibition (Williams et al 2015, 2016). In a meta-analysis by Holzman and Bridgett (2017), HRV was established as a biomarker of unspecific top-down self-regulation. Thus, there seems to be a direct line of evidence suggesting a close relationship between increased vagal function and better inhibitory control.

The ability to suppress a no-longer required response is a key feature of goal-directed and flexible behavior. Deficient inhibitory control is a central characteristic of patients with different psychiatric disorders such as attention deficit hyperactivity disorder, compulsive disorder or substance-abuse disorder (see review by Verbruggen and Logan 2009). To enhance the impaired cognitive flexibility is a major goal of current research. A large body of evidence demonstrates beneficial effects of electroencephalographic feedback training on impulsive symptomatology (see review by Sokhadze et al 2008 and Arns et al 2014).

HRV biofeedback is a non-invasive, bio-behavioral intervention, which is used to enhance vagal tone. It is based on the phenomenon of respiratory sinus arrhythmia that causes heart rate to increase during inhalation and to decrease during exhalation. By modifying breathing patterns subjects can modulate their HRV. The amplitude of heart rate variations maximally rises when the cardiovascular system is rhythmically stimulated at an optimal breathing rate that is usually about 6 breaths per minute (Song and Lehrer 2003). At this resonance frequency, blood pressure oscillations evoked by the rhythmic pumping of the beating heart initiate a cardiovascular feedback mechanism by stimulating baroreceptors. The vagal baroreflex slows heart rate when blood pressure rises and vice versa. HRV can be inducing resonance within the cardiovascular system by adapting the respiratory rhythm (Lehrer et al 2000, Vaschillo et al 2011, Lehrer and Gevirtz 2014). Breathing at the individual resonance frequency amplifies the vagal baroreceptor response (Vaschillo et al 2002, 2006, Lehrer et al 2003).

The intervention was demonstrated to restore autonomic dysfunction in patients with cardiovascular disorders (e.g. hypertension) by ‘exercising’ vagal reflexes (see review by Gevirtz (2013)). A number of studies also showed a beneficial effect in mental disorders such as depression or anxiety disorders (Gevirtz 2013). Thus, a central effect of HRV biofeedback has been speculated. Lehrer and Gevirtz (2014) highlighted the parallelism to vagal nerve stimulation which is an approved treatment option in patients with major depression or epilepsy. A pulse generator is implanted in the chest wall that stimulates vagal afferent fibers carrying impulses to the brainstem and affects brain areas known to be involved in cognition, emotion and autonomic regulation such as the locus coeruleus, frontal cortex, insula and amygdala (Henry 2002, Nemeroff et al 2006, Lehrer and Gevirtz 2014).

The technical development of smartphones, which nowadays can serve as instruments for HR assessment, analysis and real time visual feedback, allows an intuitive HRV biofeedback training at home. At the same time, the rapidly expanding market of mobile software spawned a wide variety of applications for health promotion and stress reduction (Piwek et al 2016, Peake et al 2018). However, only a small percentage of software and devices has been validated (Peake et al 2018). In pilot studies, different smartphone-based systems have been successfully used for HRV biofeedback (e.g. Munafò et al 2016, Deschodt-Arsac et al 2018). Very recently, Lin (2018) showed that HRV biofeedback training can be integrated in a psychological intervention protocol with smartphone technology. A training once a week for 4 weeks improved cardiac autonomic regulation and increased alpha-EEG activity in the frontal brain.

In the current study, we investigated whether an eight-week HRV biofeedback intervention has a lasting effect on autonomic function at rest and behavioral impulsivity. We hypothesized a linear correlation between HRV and the performance in the stop–signal task which is a measure of response inhibition. We anticipated HRV increases after biofeedback training that are accompanied by enhanced performances in the stop–signal task.

**Methods**

**Study group formation**

A total of 28 healthy participants were recruited from the local community via flyers and online advertisement and assigned pseudo randomly to two different treatment groups. One subject dropped out during the course of the intervention due to health issues, three further subjects had to be excluded subsequently due to poor completion of the instructions. Finally, 14 participants performed a biofeedback training (seven males; seven females; age: 30 ± 9 years, 22–52 years). Ten participants completed a control intervention (five males; five females; age: 30 ± 13 years, 18–55 years). Pregnancy, the intensive pursuit of endurance sports, cardiovascular diseases (e.g. hypertension, diabetes), neurological disorders (e.g. migraine, epilepsy, multiple sclerosis), or psychiatric disorders (e.g. depression, attention deficit hyperactivity disorder, anxiety disorder) were held as exclusion criteria. There was no baseline difference between the final groups in overall trait impulsivity assessed by the Barratt Impulsivity Scale (biofeedback: BIS = 55.9 ± 7.3; control: BIS = 60.1 ± 7.9) as well as its subscales (Patton et al 1995). All participants gave their informed written consent in accordance with the protocol approved by the Ethics Committee of the medical faculty of the Friedrich-Schiller University Jena.
**Intervention protocol**

The intervention took eight weeks in which participants in the biofeedback group performed an HRV biofeedback training. Five training sessions per week had to be conducted including four sessions at home and one session at the clinic’s laboratory. Subjects in the control group played one of three different jump ‘n’ run mobile games in sessions organized according to the same schedule as the biofeedback group.

Heart rate was recorded using a sensor incorporated in a belt that was tied around the chest of the subjects (H10/H7 Heart Rate Sensor; Polar Electro Oy, Kempele, Finland). Via Bluetooth the application EliteHRV (Elite HRV LLC 2017) collected data from the sensor, stored recordings and displayed heart rate. Participants in the control group recorded heart rate in the background while playing a mobile game. In the biofeedback group, heart rate was displayed on the screen of their smartphone as instantaneous visual feedback of heart rate. Participants than tried to adapt their breathing pattern to enhance heart rate oscillations as described in the following sections. All participants were instructed to send their heart rate recordings via mail after each session.

After each training session, we received the raw data acquired during that session per email from participants of both groups. The assessment of autonomic status and the behavioral experiment were conducted before the beginning of the training (T1) and after finishing the schedule (T2). One week prior to T1, an additional autonomic assessment was planned to get participants used to the procedure (T0). A synopsis of the time schedule in the biofeedback group is depicted in table 1.

**Estimation of RF**

Following the recommendations by Lehrer et al (2000), the biofeedback intervention started with the estimation of the individual RF, i.e. the breathing rhythm that maximizes HRV. In the first two weeks, participants in the biofeedback group practiced breathing at their individual RF. The app EliteHRV allowed to animate a ball in order to guide breathing at a specific rhythm in an intuitive manner. Participants were instructed to inhale when the ball extended, and to exhale when the ball contracted.

The RF was estimated in our laboratory in supine position after a resting period. A moving bar displayed on a computer screen, guided participants to breathe at frequencies of 7, 6, 5, 4.5 and 4 breaths per minute for two minutes each. Meanwhile, we recorded an electrocardiogram (ECG) and respiratory excursion of the chest and abdomen. Afterwards, the individual RF was identified as the breathing rate at which short-term HRV (the root mean of squared differences of successive heart beat intervals) was maximal. The procedure was applied at T0 for practice purposes. We assessed RF at T1, after two weeks of training and at T2 and updated the app to the current RF.

**HRV biofeedback**

From beginning of the second week, participants’ current heart rate (HR) was shown as interpolated smoothed curve on their smartphone display in addition to the pacing stimulus. Participants were briefed to observe the curve as it changed with their breathing rhythm. From week three on, participants were instructed to breathe ‘in phase’ with their HR curve by inhaling when HR ascended and exhaling when it descended. The main goal of the training was to expand the amplitudes of the HR curve in order to increase HRV.

**Assessment of autonomic function**

Resting state recordings of ECG, blood pressure, respiration, pupil size and skin conductance were conducted in supine position for 15 min. The examination room was quiet and fully shaded with a low intensity ambient light source. Additionally, participants wore headphones to be isolated from all potential surrounding noise. Via a monitor fixed over the couch a dark gray ellipse was displayed on light gray background as fixation anchor. Room temperature was controlled to 22 °C. The first five minutes were not analyzed, to allow participants to adjust to the environment.

**Data acquisition and preprocessing**

We used the MP150 system (BIOPAC Systems Inc, Goleta, CA, USA) to record multiple physiological signals simultaneously at 1000 Hz sampling rate. ECG was acquired by three electrodes attached to the chest according to an adjusted Einthoven triangle. Noninvasive blood pressure was measured continuously by the vascular unloading technique (CNAP, CNSystems Medizintechnik AG, Graz, AUS). ECG and blood pressure were band-pass filtered between 0.05 and 35 Hz. Abdominal and thoracic respiratory movement were recorded by two individual strain gauge transducers and low pass filtered at 10 Hz. Skin conductance was measured by constant voltage technique at the left hand’s palm with electrodes placed on the thenar and hypothenar eminence.

Heart beats were extracted automatically and checked manually offline. Artifacts and ectopic beats were detected and interpolated using an adaptive filtering technique (Wessel et al 2000). Diastolic and systolic blood pressure values embedded in one cardiac cycle were extracted.

Pupil size was assessed every 4 ms by the infrared camera system RED 250 (SensoMotoric Inc., Boston, MA, USA). Eye blinks expressed as sudden drops of pupil diameter were eliminated using a median filter with 1000 ms time window followed by temporal smoothing (400 ms).
Mean HR, global HRV (standard deviation of heart beat intervals, SDNN), vagal short-term HRV (root mean of squared differences of successive heart beat intervals, RMSSD) and total spectral power of HRV (Pow, spectral power at frequencies 0.001–0.4 Hz) were estimated according to the established standard procedures (Malik et al 1996). Additionally, respiratory sinus arrhythmia was calculated using the peak-valley-approach (Grossman 1992). Mean values of systolic and diastolic blood pressure and breathing rate were assessed. Baroreflex sensitivity was estimated by dual sequence method quantifying bradycardic changes of heart rate due to blood pressure increases (Wessel et al 2000). Mean pupil diameter and skin conductance level were estimated by averaging over the time of recording.

Indices of impulsivity
Participants performed the visual stop–signal task (Verbruggen and Logan 2009) implemented in Presentation® (Neurobehavioral Systems Inc., Berkeley, CA, USA). In sum, 200 Go stimuli were presented as a white ‘A’ on dark gray background for a duration of 920 ms in which subjects were instructed to respond via button press. During the 2 s inter-trial-interval, a fixation cross was shown. In 40 trials (20%), the stop signal ‘X’ followed Go stimuli with an initial delay of 400 ms. Subjects were briefed to withhold their response on appearance of the stop signal. If the subject inhibited successfully, the stop signal delay increased by 16 ms and decreased by 16 ms after failed inhibitions. Using this procedure, a representative delay can be estimated that is required to succeed in withholding a response in approximately half of the stop trials. The characteristic stop–signal response time (SSRT), which can be used as indicator of impulsivity, was calculated by subtraction of the final stop signal delay from the median of all Go reaction times (GoRT) (Verbruggen and Logan 2009). A low SSRT indicates a high capacity to inhibit a response that has already been initiated and, thus, less impulsive behavior. Participants conducted the experiment in sitting position after a short practice session (ten trials).

Statistical analysis
Each variable was checked for normality of its distribution by the Kolmogorov–Smirnov test. RMSSD, baroreflex sensitivity and HRV spectral power were log-transformed to achieve normal distribution. Bivariate linear relationships between behavioral measures of impulsivity (i.e. mean GoRT and SSRT) and autonomic indices were assessed by Pearson’s correlation coefficients and respective p-values. In correlative analyses, statistical thresholds were corrected for multiple comparisons using false discovery rate (Benjamini and Hochberg 1995).

Paired t-tests were applied to investigate the effect of the intervention in each group. In a more exploratory manner, we contrasted the starting condition at T1 of responders and non-responders to the biofeedback training. We identified responders by a positive change of RMSSD from T1 to T2 indicating an increase of vagal HRV after the biofeedback training.

Results
Correlation of performance in the stop–signal task and autonomic status
We found a relationship between the outcome of the stop–signal task and markers of autonomic function. Standard HRV parameters were negatively correlated to the GoRT and SSRT indicating higher levels of inhibitory control in participants with high HRV (see table 2). The relation of respiratory sinus arrhythmia and SSRT is depicted in figure 1 (left).
In this study, we investigated the effect of a smartphone-based HRV biofeedback intervention over eight weeks on autonomic function and impulsivity in healthy subjects. We found significant increases of short-term HRV by 33% and baroreflex function by 21% in the biofeedback but not in the control group. Although a significant linear correlation of HRV and the performance in the stop-signal task was found, the biofeedback intervention...
A Schumann et al led to no changes of behavioral impulsivity. Our results suggest a beneficial influence of HRV biofeedback on resting cardiovascular regulation. Lower levels of vagally modulated HRV have been associated with increased cardiovascular morbidity and mortality (Tsuji et al 1996, Thayer and Lane 2007). Hillebrand et al (2013) reported that healthy subjects with diminished resting HRV have a 32%–45% increased risk to suffer from a first cardiovascular event. Resting heart rate and HRV were demonstrated to predict cardiovascular disease as well as cardiac and overall mortality (Jensen et al 2012, 2013, Nanchen et al 2013). A decline of HRV with increasing age is well documented and might precede age-related impairment of cardiovascular regulation (Agelink et al 2001, 2005, De Meersman and Stein 2007, Stein et al 2009).

Therefore, interventions that enhance HRV are an important tool to promote physical health. HRV biofeedback seems to be an obvious choice as intervention on cardiovascular autonomic regulation. However, the effect of a long-lasting training on autonomic status in healthy controls is not well documented. In their review, Wheat and Larkin (2010) concluded that there is only little evidence that HRV biofeedback results in short-term and long-term HRV improvements.

Randomized controlled trials like this study are gold standard instruments to validate a substantial intervention effect. However, we did not compare the effects of both interventions on autonomic function directly due to the limited sample sizes and statistical power. Thus, larger experimental groups are needed to replicate enhanced

| Parameter                          | Non-responder | Responder | Significance |
|------------------------------------|---------------|-----------|--------------|
| GoRT (ms)                          | 441 ± 99      | 479 ± 123 | 0.578        |
| SSRT (ms)                          | 183 ± 23      | 209 ± 31  | 0.133        |
| HR (1 min⁻¹)                       | 68.1 ± 7.1    | 75.8 ± 9.4| 0.141        |
| SDNN (ms)                          | 77.1 ± 18.6   | 47.3 ± 21.9| 0.025       |
| RMSSD (ms)                         | 59.5 ± 22.5   | 27.6 ± 17.9| 0.019       |
| Pow (ms²)                          | 5.86 ± 3.31   | 2.49 ± 2.22| 0.041       |
| BR (1 min⁻¹)                       | 11.8 ± 5.0    | 14.4 ± 5.5| 0.399        |
| RSA (ms)                           | 147.2 ± 49.7  | 73.9 ± 63.2| 0.046       |
| MAP (mmHg)                         | 87.8 ± 4.3    | 87.9 ± 8.9| 0.967        |
| BRS (ms mmHg⁻¹)                    | 25.4 ± 21.8   | 12.2 ± 8.9 | 0.148       |
| SCL (µS)                           | 6.6 ± 4.0     | 14.5 ± 9.8| 0.057        |
| DIA (mm)                           | 3.98 ± 0.57   | 4.69 ± 0.74| 0.091       |

GoRT: mean reaction times in Go trials of stop signal task; SSRT: stop signal reaction time; HR: mean heart rate; SDNN: standard deviation of heart beat intervals; RMSSD: root mean squared differences of successive heart beat intervals; Pow: total power of heart rate spectral density; BR: breathing rate; RSA: respiratory sinus arrhythmia; MAP: mean arterial pressure; BRS: baroreflex sensitivity; SCL: skin conductance level; DIA: pupil diameter. Bold p-values indicate a significant paired t-test (p < 0.05).
resting cardiovascular function due to the biofeedback intervention. In our sample, five participants did not respond to the training in terms of an HRV increase (positive change of RMSSD). Compared to responders, non-responders had higher baroreflex sensitivity and HRV levels prior to the intervention. Therefore, it seems that subjects with lower vagal function profited most from the biofeedback training.

To our best knowledge, this is the first study that assessed the influence of HRV biofeedback on behavioral impulsivity. Before the onset of the intervention, performance in the stop–signal task and HRV markers correlated linearly. In our sample, participants with high respiratory sinus arrhythmia, slow breathing rate and high HRV showed faster SSRT indicating high inhibitory control and cognitive flexibility. These results are in line with relevant literature suggesting HRV as a marker of efficient cognitive functioning (Thayer et al 2009).

Despite this relationship, we found no changes of task performance that accompanied autonomic changes due to HRV biofeedback. In both groups mean GoRT increased marginally after the intervention suggesting a more cautious execution of the task at T2. Whereas the SSRT in the control group increased almost simultaneously, it slightly decreased in the biofeedback group. However, due to a high inter- and intra-individual variability no statistically significant changes were observed.

The stop–signal task is a widely popular paradigm to study response inhibition as it focuses on the latency of the stop process. Although the SSRT is of great importance when investigating inhibitory control, it indicates only one facet of impulsivity, i.e. the motor domain. However, the SSRT showed poorer test–retest reliabilities in comparison to other measures of response inhibition (Wöstmann et al 2013). Our future studies might as well assess the cognitive aspect of inhibitory control for a more comprehensive understanding of the relation between autonomic function and impulsivity.

Notwithstanding, our results highlight the potential of HRV biofeedback to enhance cardiovascular status in healthy control. Especially, subjects with subclinical cardiovascular impairment might profit from this type of training. The use of smartphones for recording, analysis and feedback of heart rate facilitates an easy and widely unsupervised training at home.

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References

Agelink M W, Majewski T, Akila F, Zeit T and Ziegler D 2001 Standardized tests of heart rate variability: normal ranges obtained from 309 healthy humans, and effects of age, gender, and heart rate Clin. Auton. Res. 11 99–108

Agelink M W, Sanner D and Ziegler D 2005 Age-related changes of the human autonomic nervous system Neuroimmune Biol. 4 215–31

Arns M, Heinrich H and Strehl U 2014 Evaluation of neurofeedback in ADHD: the long and winding road Biol. Psychol. 95 108–15

Benjamini Y and Hochberg Y 1995 Controlling the false discovery rate: a practical and powerful approach to multiple testing J. R. Stat. Soc. 57 289–300

Deschodt-Arsac V, Lalanne R, Spiluttini B, Bertin C and Arsac L M 2018 Effects of heart rate variability biofeedback training in athletes exposed to stress of university examinations PLoS One 13 e0201388

De Meersman R E and Stein P K 2007 Vagal modulation and aging Biol. Psychol. 74 165–73

Gevirtz R 2013 The promise of heart rate variability biofeedback: evidence-based applications Biofeedback 41 110–20

Grossman P 1992 Respiratory and cardiac rhythms as windows to central and autonomic biobehavioral regulation: selection of window frames, keeping the panes clean and viewing the neural topography Biol. Psychol. 34 131–61

Hansen A L, Johnsen B H and Thayer J F 2003 Vagal influence on working memory and attention Int. J. Psychophysiol. 48 263–74

Henry T R 2002 Therapeutic mechanisms of vagus nerve stimulation Neurology 59 53–64

Hillebrand S, Gast K B, Deutscher R, Swenne C A, Middeldorp S, Rosendaal F R and Dekkers O M 2013 Heart rate variability and first cardiovascular event in populations without known cardiovascular disease: meta-analysis and dose-response meta-regression Europace 15 142–9

Holman J B and Bridgert D J 2017 Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: a meta-analytic review Neurosci. Biobehav. Rev. 74 233–55

Jensen M T, Marott J L, Allin K H, Nordestgaard B G and Jensen G B 2012 Resting heart rate is associated with cardiovascular and all-cause mortality after adjusting for inflammatory markers: the Copenhagen City Heart Study Eur. J. Prev. Cardiol. 19 102–8

Jensen M T, Suaud-cani P, Heim HO and Guntelberg F 2013 Elevated resting heart rate, physical fitness and all-cause mortality: a 16-year follow-up in the Copenhagen Male Study Heart 99 882–7

Lehrer P M and Gevirtz R 2014 Heart rate variability biofeedback: how and why does it work? Frontiers Psychol. 5 756

Lehrer P M, Vaschillo E and Vaschillo B 2000 Resonant frequency biofeedback training to increase cardiac variability: rationale and manual for training Appl. Psychophysiol. Biofeedback 25 177–91

Lehrer P M et al 2003 Heart rate variability biofeedback increases baroreflex gain and peak expiratory flow Psychosom. Med. 65 796–805

Lin I M 2018 Effects of a cardiorespiratory synchronization training mobile application on heart rate variability and electroencephalography in healthy adults Int. J. Psychophysiol. 134 168–77
Malik M, Bigger J, Camm A and Kleiger R 1996 Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology Eur. Heart J. 17 554–81

Mathewson K J, Drmic I E, Jetha M K, Bryson S E, Goldberg J O, Hall G B, Santesso S J and Schmidt L A 2011 Behavioral and cardiac responses to emotional stroop in adults with autism spectrum disorders: influence of medication Autism Res. 4 98–108

Munafo M, Patron E and Palomba D 2016 Improving managers’ psychophysical well-being: effectiveness of respiratory sinus arrhythmia biofeedback Appl. Psychophysiol. Biofeedback 41 129–39

Nanchen D et al 2013 Resting heart rate and incident heart failure and cardiovascular mortality in older adults: role of inflammation and endothelial dysfunction: the PROSPER study Eur. J. Heart Fail. 15 581–8

Nemeroff C B, Mayberg H S, Krahl S E, McNamara J, Frazer A, Henry T R, George M S, Charney D S and Brannan S K 2006 VNS therapy in depression: a double-blind randomized controlled trial Neuropsychopharmacology 31 1345–55

Peake J M, Kerr G and Sullivan J P 2018 A critical review of consumer wearables, mobile applications, and equipment for providing biofeedback, monitoring stress, and sleep in physically active populations Frontiers Physiol. 9 743

Piwek L, Ellis D A, Andrews S and Joinson A 2016 The rise of consumer health wearables: promises and barriers PLoS Med. 13 e1001953

Robbins M A, Elias M F, Elias P K and Budge M M 2005 Blood pressure and cognitive function in an African–American and a Caucasian–American sample: the Maine–Syracuse Study Psychosom. Med. 67 707–14

Ruíz-Padial E, Solers J J III, Vila J and Thayer J F 2003 The rhythm of the heart in the blink of an eye: emotion-modulated startle magnitude covaries with heart rate variability Psychophysiology 40 306–13

Sokhadze T M, Cannon R L and Trudeau D L 2008 EEG biofeedback as a treatment for substance use disorders: review, rating of efficacy, and recommendations for further research Appl. Psychophysiol. Biofeedback 33 1–28

Song H S and Lehrer P M 2003 The effects of respiratory rates on heart rate and heart rate variability Appl. Psychophysiol. Biofeedback 28 13–23

Stein P K, Barzilay J I, Chaves P H M, Dimitrovich P P and Gottdiener J S 2009 Heart rate variability and its changes over 5 years in older adults Age Ageing 38 212–8

Sutterlin S, Herbert C, Schmitt M, Kubler A and Vogele C 2011 Overcoming selfishness: reciprocity, inhibition, and cardiac-autonomic control in the ultimatum game Frontiers Psychol. 2 173

Thayer J F, Hansen A L, Saus-Rose E and Johnsen B H 2009 Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health Ann. Behav. Med. 37 141–53

Thayer J F and Lane R D 2007 The role of vagal function in the risk for cardiovascular disease and mortality Biol. Psychol. 74 224–42

Tsuji H, Larson M G, Venditti F J, Manders E S, Evans J C, Feldman C L and Levy D 1996 Impact of reduced heart rate variability on risk for cardiac events Circulation 94 2850–5

Vaschillo E, Lehrer P, Rishe N and Konstantinov M 2002 Heart rate variability biofeedback as a method for assessing baroreflex function: a preliminary study of resonance in the cardiovascular system Appl. Psychophysiol. Biofeedback 27 1–27

Vaschillo E G, Vaschillo B and Lehrer P M 2006 Characteristics of resonance in heart rate variability stimulated by biofeedback Appl. Psychophysiol. Biofeedback 31 129–42

Vaschillo E G, Vaschillo B, Pandina R J and Bates M E 2011 Resonances in the cardiovascular system caused by rhythmical muscle tension Psychophysiology 48 927–36

Verbruggen F and Logan G D 2009 Models of response inhibition in the stop–signal and stop–change paradigms Neurosci. Biobehav. Rev. 33 647–61

Wessel N, Voss A, Malberg H, Ziehmann C, Voss H U, Schirdevan A, Meyerfeldt U and Kurths J 2000 Nonlinear analysis of complex phenomena in cardiological data Herzschrittmacherther. Elektrophysiol. 11 159–73

Wheat A L and Larkin K T 2010 Biofeedback of heart rate variability and related physiology: a critical review Appl. Psychophysiol. Biofeedback 35 229–42

Williams D P, Cash C, Rankin C, Bernardi A, Koenig J and Thayer J F 2015 Resting heart rate variability predicts self-reported difficulties in emotion regulation: a focus on different facets of emotion regulation Frontiers Psychol. 6 261

Williams D P, Thayer J F and Koenig J 2016 Resting cardiac vagal tone predicts intra-individual reaction time variability during an attention task in a sample of young and healthy adults Psychophysiology 53 1843–51

Wöstmann N M, Aichert D S, Costa A, Rubia K, Möller H-J and Ettenger U 2013 Reliability and plasticity of response inhibition and interference control Brain Cogn. 81 82–94