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The association between individual differences in executive functioning and resting high-frequency heart rate variability

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ABSTRACT

Both resting high-frequency heart rate variability (HF-HRV) and executive functioning (EF) are individual differences implicated in vulnerability to a wide range of adverse outcomes. The overlapping set of associations, along with theoretical models positing connections between the brain regions subserving the executive functions and the parasympathetic nervous system, suggest that the two factors should be correlated. Seeking to address limitations in prior research, the current study examined the association between EF, measured comprehensively with individually-administered neuropsychological tests and controlling for lower-order cognitive processes, and resting physiology, measured with impedence cardiography, in healthy, community participants (68% female; mean age = 27, SD = 6.5). Results confirmed a significant association between EF and resting HF-HRV, but no association with resting state sympathetic nervous system activation (pre-ejection period). These findings may inform future investigation of transdiagnostic mechanisms related to these two individual difference factors.

Identifying individual differences in vulnerability and resilience to adverse mental and physical health outcomes informs our understanding of developmental mechanisms and aids in the identification of prevention and intervention strategies. There is a large and growing literature framing such individual differences within the broad umbrella category "self-regulation," as well as an emerging interest in characterizing transdiagnostic vulnerability (e.g., NIH Research Domain Criteria [RDoC] framework for mental illnesses). Critically, the construct of self-regulation has been defined in a variety of ways and many related terms have been used, often in non-overlapping research literatures. Indeed, self-report measures of "self-regulation" and related constructs (e.g., self-control, attentional control, emotion regulation, effortful control) are used frequently, a practice with significant limitations given weak associations with objective cognitive measures (cf. Williams, Rau, Suchy, Thorgusen, & Smith, 2017). Thus, identification of more reliable, objective assessment approaches is an important endeavor. To this end, individual differences in executive functioning (EF) have been conceptualized as reflecting *behavioral self-regulation*, conferring risk and resilience, as well as predicting health behavior and chronic illness (Williams, Suchy, & Rau, 2009; Williams, Tinajero, & Suchy, 2017). Similarly, resting high-frequency heart rate variability (HF-HRV; also referred to as "vagal tone" or respiratory sinus arrhythmia [RSA]) is an individual difference factor sometimes associated with the higher-order construct *self-regulatory capacity*. Prior research indicates that high frequency cardiac rhythms are mediated primarily by vagal innervation of the sinus node; hence, resting HF-HRV is considered an indirect indicator of vagally-mediated parasympathetic nervous system activity (see Berntson et al., 1997 for review). Like EF, resting HF-HRV is associated with a wide range of mental and physical health outcomes (e.g., Beauchaine & Bell, 2019; Beauchaine & Thayer, 2015; Thayer & Sternberg, 2006). Neurobehavioral models of self-regulation (Porges, 2007; Thayer & Lane, 2007, 2009) posit an overlap between the brain regions subserving EF and the parasympathetic nervous system. Specifically, parasympathetic activity is associated with connectivity among midline brain structures, including ventromedial prefrontal cortex and cingulate cortex, structures well known to subserve EF (Guo et al., 2016; Kumral et al., 2019; Palma & Benarroch, 2014).

Importantly, both EF and resting HF-HRV have demonstrated heritability and both have been characterized as vulnerability factors for many of the same behavioral and health endpoints, suggesting there should be a significant association between the two factors (see

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Beauchaine & Bell, 2019; Thayer & Lane, 2009; Williams, Tinajero et al., 2017 for reviews). Prior research investigating this association has yielded equivocal findings, but many studies have significant limitations, particularly in the assessment of EF. The purpose of the current study was to address the limitations of previous studies by implementing comprehensive EF assessment in a well-characterized healthy young adult sample.

1. Definitions and background

Executive functioning is an umbrella term that refers to the set of neurocognitive processes that allow one to engage in goal-directed behavior by employing novel problem solving, modification of behavior in response to environmental changes, generating strategies for complex actions, and the ability to override pre-potent behavioral and emotional responses to more successfully engage in goal-directed behavior (Duffy, Campbell, Salloway, & Malloy, 2001; Stuss, Alexander, & Benson, 1997; Suchy, 2009, 2015). A variety of terms have been used in the literature to describe the multitude of components that are presumed to fall under the EF umbrella (one literature review identified 68 subcomponents, Packwood, Hodgetts, & Tremblay, 2011), and dozens of definitions and models have been proposed (for review, see Karr et al., 2018; Suchy, 2015, pp. 5–7). Although in recent years there has been much focus on a model of EF that contains three main components (inhibition, shifting, and updating in working memory; Miyake et al., 2000), the degree to which this model reflects a comprehensive and reliable structure of EF has been questioned (Karr et al., 2018). In fact, in their systematic review and re-analysis of factor-analytic models of EF, Karr et al. (2018) found poor convergence of results across samples, although they did find support for both the diversity and the unity of the EF construct. Given the unity/diversity conceptualization of EF, it should not be surprising that, on the one hand, a large number of brain regions are involved in different components of EF (for a review, see Suchy, 2015), and, on the other hand, a common overarching network is involved in *all* EF functions (Niendam et al., 2012). This common network includes the prefrontal cortex (PFC), parietal, and the anterior cingulate cortices (Braver, Ruge, Cabeza, & Kingstone, 2006; Collette & van der Linden, 2002; Duffy et al., 2001; Osaka, 2007; Stuss et al., 1997). Relevant to self-regulatory processes, the anterior cingulate aspect of this network has been associated with modulation of the autonomic nervous system (Critchley, 2005).

The parasympathetic nervous system influences cardiac function via the vagus nerve, which has rich connections to the PFC. There is evidence that parasympathetic activation is partly reflected in heart rate variability (HRV)—the variation in time interval between heart beats. Although HRV can be quantified in a variety of ways, the use of spectral analysis to isolate high frequency heart rate variability (HF-HRV) is thought to better indicate parasympathetic nervous system activity (e.g., Berntson et al., 1997). Importantly, HF-HRV is associated with PFC activity (Lane, Reiman, Ahern, & Thayer, 2001; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012). That is, EF and aspects of parasympathetic nervous system functioning are co-localized in this brain region. Indeed, both the PFC and the anterior cingulate cortices figure prominently in recent models of self-regulation, including the Neurovisceral Integration Model (Thayer & Lane, 2007, 2009) and Polyvagal Theory (Porges, 2007). Specifically, the PFC is hypothesized to support not only adaptive self-regulatory behavior, but also stress-dampening physiological activity through parasympathetic nervous system mechanisms. Thus, higher resting or tonic HF-HRV has been considered to reflect, in part, the higher-order construct *self-regulatory capacity* (Porges, 2007; Thayer & Lane, 2007, 2009), and has been associated with a variety of inter-related constructs including “self-regulation” (Holzman & Bridgett, 2017), “self-control” (Zahn et al., 2016), “emotion regulation” (Balzarotti, Biassoni, Colombo, & Ciceri, 2017) and has been framed as a transdiagnostic vulnerability factor for emotion dysregulation (Beauchaine & Bell, 2019).

2. Prior examinations of the association between EF and resting HF-HRV

Previous studies examining the association between EF and resting HF-HRV have been equivocal. Among studies finding significant association, Stenfors et al. (2016) examined components of EF, assessed with individually administered neuropsychological tests, and a variety of autonomic indicators. They report significant associations between some HRV measures and components of EF; however, most associations dropped to nonsignificance when age was controlled. Williams, Thayer, and Koenig (2016) found that resting HF-HRV predicted reaction time variability during an attention task, presumably indexing EF in a sample of young, healthy adults. In a sample of male sailors, participants in a high resting HF-HRV group (by median split) performed better on cognitive tasks with an executive component than did participants lower in resting HF-HRV (Hansen, Johnsen, & Thayer, 2003; Hansen, Johnsen, & Thayer, 2003). In a large sample, Jennings, Allen, Gianaros, Thayer, and Manuck (2015) examined the association between resting HF-HRV and performance on a variety of neuropsychological tests. Although the associations were not strong, performance on the only true executive function task in the battery—the Stroop test—was significantly associated with resting HF-HRV. Kemp et al. (2016) reported that resting HF-HRV was associated with EF both directly (via performance on the Trail Making test), and indirectly (via insulin resistance and carotid intima-media thickness). One recent study that sought to account for several potential confounding factors including sex, body mass index (BMI), and trait impulsivity reported that two measures of inhibitory control were positively related to resting HF-HRV (Ottaviani et al., 2018). In addition, one study that examined resting pre-ejection period (PEP) as well as resting HF-HRV reported that both measures were independently associated with an auditory selective attention task reflecting effortful top-down allocation of attentional resources, typically thought to be reliant on EF (Giuliano et al., 2018). Examination of participants in the Coronary Artery Risk Development in Young Adults study revealed that one index of HRV—higher quartile of standard deviation of normal-to-normal intervals (SDNN)—predicted EF assessed by Stroop task performance 3 years later (Zeki Al Hazzouri, Elfassy, Carnethon, Lloyd-Jones, & Yaffe, 2017). The lack of concurrent measurement of EF means that the direction of causal effects should not be assumed, however.

In contrast to the studies reviewed above, Kimhy et al. (2013) found no significant association between resting HF-HRV and EF, using data from the MIDUS study. There were a variety of limitations, however, including phone administration—a method known to reduce test reliability (not reported), and EF assessment of limited scope. Although the phone interview included some EF tests (category fluency and task switching), it also included non-EF tests of processing speed. Critically, there was a variable degree of time lag between cognitive and physiological assessments, with an average of two years lag between EF and HF-HRV assessments. Also using MIDUS data, Mann, Selby, Bates, and Contrada (2015) used a structural equation modeling approach to examine EF and resting-HF-HRV. Although the constructs were significantly associated in the initial structural model, the association dropped to non-significance when age was included as a covariate.

Taken together, the literature suggests that although there has been some support for an association between individual differences in resting HF-HRV and EF, the strength of reported association is often weak and, in some studies, not significant. This is exemplified by a recent meta-analysis of HRV and “self-control” studies in which aspects of EF were specifically explored (Zahn et al., 2016). These authors report a significant effect for tasks associated with inhibition, but not for shifting and updating, in the set of EF tasks available for meta-analysis.

Importantly, there are a number of limitations in prior studies, including (a) use of cognitive tasks that are not specifically executive (e.g., processing speed) and (b) the use of single tests of EF of unknown reliability and without consideration of non-EF aspects of performance.

This latter point pertains to the notion that cognition is organized in a hierarchical fashion (Stuss, Picton, & Alexander, 2001), which means that *higher-order processes* (such as EF) depend on *lower-order processes* (such as the ability to perceive a stimulus, or the speed at which a response is generated). These lower-order processes necessarily confound any performance on EF tests. In fact, as reported above, significant associations between EF and HF-HRV dropped out in some studies after controlling for age, suggesting that lower-order cognitive processes (e.g., speed of processing) that are strongly related to both age and to performance on EF tests may have been responsible for the initially observed associations. Thus, an important caveat in assessment of EF is that lower-order processes, such as comprehension of test instructions, perception of stimuli, speed of processing, or speed of motor or verbal output, must be accounted for before interpretation of results can be made (for a comprehensive review, see Suchy, Niermeyer, & Ziemnik, 2017; Suchy, Ziemnik, & Niermeyer, 2017). Notably, HF-HRV declines with age (Tsuji, Evans, & Levy, 1996), also likely contributing to the effects of age on the association with EF.

In addition, single tests of EF, particularly when computer- or phone-administered, tend to have lower reliabilities; in contrast, composites of multiple EF tests have been shown to be more reliable than single scores (Suchy, 2015). The extent to which low reliability has been a limitation in prior studies is difficult to evaluate, given that reliability of cognitive tests is often not reported. There may also be developmental considerations. Whereas having a wide-age range in a sample would often be a strength, models of self-regulation positing integration of prefrontal cortex functioning and vagal tone suggest that the fidelity of this association may degrade with aging, a supposition with some empirical support (e.g., Sakaki et al., 2016). Consequently, examination of younger healthy adults may be more likely to yield the hypothesized association.

3. The current study

The aim of the current study was to address three limitations of prior studies examining the association between EF and resting HF-HRV: (1) Potential attenuation of the resting HF-HRV-EF association in older adults, (2) limited or unknown reliability of EF measures, and (3) the possibility that prior findings could be explained by lower-order cognitive processes that are known to be necessary for EF performance. To these ends, we (1) utilized a young adult community sample, screened for a wide range of physical and mental health problems, (2) assessed EF with individually-administered neuropsychological tests from the Delis-Kaplan Executive Function System battery (D-KEFS; Delis, Kaplan, & Kramer, 2001), using a composite of 8 D-KEFS scores to maximize reliability (Suchy, 2015), and (3) included the D-KEFS task conditions that are designed specifically to allow for the control of lower-order non-EF aspects of performance. Impedence cardiography was utilized to examine the specificity of EF associations with resting HF-HRV. It was hypothesized that individual differences in EF (after controlling for lower-order component processes) would be significantly associated with resting HF-HRV, thought to partly reflect parasympathetic nervous system functioning, versus PEP, widely considered to reflect sympathetic nervous system activation. As points of comparison, associations between HF-HRV and EF subtests were also examined, as well as working memory performance, with the prediction that these associations would be more modest than that with the EF residual composite score (i.e., controlling for lower order cognitive processes). Finally, given the extensive prior literature framing resting HF-HRV and EF as self-regulatory individual differences, associations with self-report measures presumed to tap self-regulation (e.g., attentional control, emotion regulation) were also examined.

4. Methods

4.1. Participants

Participants were 79 healthy adults (32% male; mean age = 27 years, SD = 6.5) recruited from undergraduate psychology courses and the greater Salt Lake City community. Participants were recruited for a larger study focused on individual differences in stress risk and resilience. The screening criteria were extensive to ensure participants who did not yet have significant mental or physical health problems and to remove confounding factors for performance on cognitive tests. Exclusionary criteria included age beyond 20–45 years; primary language other than English; left hand dominance (given the focus on cognitive functioning); symptoms indicative of clinical insomnia; visual impairments that could interfere with reading or computerized task performance; arm impairments that could interfere with cognitive task performance; current pregnancy; history of brain trauma, seizures, brain tumor, stroke or aneurysm, brain surgery, heart surgery, multiple sclerosis, major orthopedic surgery, hypertension, pulmonary disorder, or renal failure; and current use of cardiovascular, neuroleptic, or hypnotic medications (e.g., beta blockers). Participant characteristics are shown in Table 1. Participants were asked to avoid caffeine, nicotine, and physical exertion (e.g., aerobic exercise) two hours prior to the laboratory assessment session.

4.2. Procedure

As part of a larger study, participants completed informed consent and eligibility screening. Data for the current study come from a baseline laboratory assessment of resting/tonic physiology and executive cognitive functioning, as well as a battery of self-report questionnaires, along with nighttime ratings of daily self-regulation during a 3-day ecological momentary assessment.

4.3. Measures: performance-based EF and working memory

Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001). As reviewed earlier, EF is a complex construct consisting of an unknown number of processes. Many models of EF have been proposed, but none is universally accepted. Recent review and re-analysis by Karr et al. (2018) supports the notion that, on the one hand, EF is a construct consisting of diverse components, and, on the other hand, that there is unity among these components such that they are all related. Consistent with the notion of EF unity, we have been using a single composite of several EF tests across a number of studies and across a range of populations (from adolescents to older adults). Our rationale for using a

Table 1
Participant Characteristics.

Variable	*M*	SD	Range
Age (years)	27.5	6.5	20-45
Education (years)	16.2	2.3	10- 23
Body Mass Index	25.4	5.5	17.2-44
Number of minutes exercising per week	358.2	282.05	0-1350
Number of alcoholic drinks per week	1.84	2.84	0-15
Number of caffeinated drinks per week	6.23	6.1	0-28
Smoking or user of tobacco products (%)			
Yes	5 (6.3%)		
No	73 (92.4%)		
Missing Data	1 (1.3%)		
Race (%)			
White/Caucasian	72 (91.1%)		
Asian	4 (5.1%)		
Other	1 (1.3%)		
Missing data	2 (2.5%)		

M = mean; SD = standard deviation.

single composite score is as follows: First, it is well documented that measures of EF have lower reliabilities than other types of cognitive tests (Calamia, Markon, & Tranel, 2013). However, well-constructed composites are psychometrically more reliable than single scores (Ettenhofer, Hambrick, & Abeles, 2006) and we have, in fact, consistently found that our composite is not only reliable (Berg et al., 2018; Franchow & Suchy, 2015, 2017; Huebner, McGarrity, Perry, Smith, & Suchy, 2018; Niermeyer, Suchy, & Ziemnik, 2017; Suchy, Niermeyer, Franchow, & Ziemnik, 2018; Suchy, Holmes et al., 2018; Suchy et al., 2016; Wiebe, Baker, Suchy, Stump, & Berg, 2018), but also that the reliability of the composite is higher than the mean or median reliabilities of single scores (Suchy, 2015). Second, a single composite score decreases the number of analyses, thereby decreasing the risk of type 1 error. Third, a single composite score is more stable as a construct than composites generated via factor-analyses (Karr et al., 2018), the results of which are known to vary based on the population used (Delis, Jacobson, Bondi, Hamilton, & Salmon, 2003). Fourth, consistent use of the same composite across all our studies precludes “cherry-picking” from among several EF tests. Lastly, consistent with the strength of this approach, we have found that the single composite score yields stronger results than the use of individual scores (Tinajero et al., 2018).

Four subtests were administered from the D-KEFS from which 8 conditions reflecting central components of EF were used to create an EF composite. The subtests and their components used to create the EF composite were: Trail Making (Letter Number Sequencing completion time), Verbal Fluency (Letter and Category correct responses), Design Fluency (number of correct responses for three conditions), and Color-Word Interference (Inhibition and Inhibition/Switching completion times). Age-corrected scaled scores were generated for each subtest based on test manual and all 8 conditions were averaged to create an EF composite. Overall, these 8 task conditions assess set-maintenance, inhibition, cognitive control, initiation, and generative fluency.

Importantly, cognitive functions are organized hierarchically, with higher-order processes like EF relying on lower-order processes (Stuss et al., 2001). Consistent with our past research (Berg et al., 2018; Franchow & Suchy, 2015, 2017; Huebner et al., 2018; Niermeyer et al., 2017; Suchy, Niermeyer et al., 2018; Suchy, Holmes et al., 2018; Suchy et al., 2016; Wiebe et al., 2018), to control for non-EF aspects of the composite, a lower-order processes composite was created by averaging the age-corrected scores of six conditions including Color Naming and Word Reading from the Color-Word Interference Test, and Visual Scanning, Number Sequencing, Letter Sequencing, and Motor Speed from the Trail Making Test. Overall, these six task conditions assess graphomotor speed, speed of verbal output, visual scanning and perception, and simple sequencing abilities. Next, similar to the approach used by Karr, Hofer, Iverson, and Garcia-Barrera (2018), the lower-order processes were controlled by removing their variance from the EF composite, resulting in an unstandardized residual of the EF composite, reflecting EF without confounding lower-order processes. The unstandardized residual of the EF composite was used in all subsequent analyses (referred to as “EF residual” hereafter). Of note, it could be argued that the exact demarcation between where EF ends and lower-order processes begin is not known and thus it is possible that the presently employed procedures might remove some of the EF variance. In fact, we have found that some tasks that are typically considered non-executive begin to progressively tap EF with increasing age (Niermeyer et al., 2017). However, in the present study, all participants were young and it is unlikely that a substantive amount of EF variance was removed due to this procedure, while at the same time we ascertained that we were tapping the EF construct, rather than other, lower-order processes (note: the correlation between the non-residualized EF score and the nonexecutive composite was $r = .63$, $p < .0001$). Cronbach’s alphas were .75 for the executive composite and .81 for the nonexecutive composite, which is comparable to reliabilities in our prior research using these composites in other young adult samples (Franchow & Suchy, 2015; Huebner et al., 2018; Suchy et al., 2016).

Wechsler Adult Intelligence Scale (WAIS)-Working Memory Composite. Although all tests of EF used in this study tax, at least to some extent, working memory (i.e., the ability to hold and manipulate information in mind, sometimes also referred to as “immediate short-term memory”), we also administered a separate set of tasks that more purely tap the working memory construct. The reason for this is that some research relies on tests of working memory as the sole index of EF, yet we have previously found that working memory performance yields different results when compared to a more comprehensive EF assessment (Franchow & Suchy, 2015). In this study, working memory was measured using two subtests from the WAIS-III (Psychological Corporation, 1997). Scaled scores (i.e., age-corrected) from the Arithmetic, Digit Span, and Letter-Number Sequencing subtests were averaged to create a working memory composite score, Cronbach’s alpha = 0.65.

4.4. Measures: resting psychophysiology

Impedance Cardiography. A MW1000A ambulatory impedance cardiography and heart rate variability monitor (Mindware Technologies, Gahanna, Ohio) was used to obtain both electrocardiogram (ECG), respiration rate and amplitude during a resting baseline period (see Ernst, Litvack, Lozano, Cacioppo, & Bernston, 1999; Houtveen, Groot, & De Geus, 2006; Seppä, Viik, & Hyttinen, 2010 for examination of the validity of respiration assessment with impedence cardiography). Prior research suggests that resting state HRV is recorded best under conditions of spontaneous breathing (e.g., Larsen, Tzeng, Sin, & Galletly, 2010; Bertsch, Hagemann, Naumann, Schächinger, & Schulz, 2012). Respiration is most identifiable in the Z_0 signal. The Z_0 signal was low pass filtered and linearly detrended to remove the DC offset and any high frequency noise. After filtering and detrending, the frequency content of the Z_0 signal correlates closely with actual respiration. ECG data were collected from participants using three spot electrodes placed in the standard lead II configuration. The ECG was measured continuously at a sampling rate of 500 Hz.

Electrodes were applied to participants prior to the start of a resting 10-minute baseline period. Participants were instructed to sit quietly in an arm chair with both feet uncrossed and placed on the ground. Participants were instructed to keep their eyes open during the resting baseline. The first 5 min of the baseline period served as an acclimation period. Data from the last 5 min of the 10-minute baseline period were used to compute HF-HRV and PEP, with ECG analyses performed for one-minute periods.

The raw ECG data were inspected using automated software and then visually inspected according to the guidelines for detecting artifacts and abnormal beats (Berntson, Quigley, Jang, & Boysen, 1990). For the purpose of the current study, HRV Analysis Software 3.0.12 (Mindware Cardiography system, Gahanna, Oh) was used to verify, edit, and summarize cardiovascular data. The same HRV analysis software was used to derive heart rate variability (ms^2/Hz) by applying Fourier analysis to the interbeat interval function (IBI function – the time between successive R-peaks) from the ECG. The IBI function was time sampled at 4 Hz to produce an equidistant time series. Time series analysis of IBI function using spectral approaches assumes that data points are equally spaced. Successive IBI functions are spaced unevenly in time, and thus must be subjected to methods to derive an equal time series. A sampling rate of 4 Hz was used to sufficiently capture HF rhythms at high respiratory rates.

The equal time series was detrended, end tapered, and submitted to a fast Fourier Transformation according to procedures outlined by Berntson et al. (1997). A Hamming window was used for tapering the time series. The detrending process involves the application of a second-order polynomial to the IBI function. Fourier analysis was used to decompose heart rate variability within the high-frequency range. The high-frequency component of HRV consists of the (presumed) parasympathetically-driven oscillations corresponding to the range of respiratory frequencies (0.12-0.40 Hz). Baseline HF-HRV was calculated by averaging across the last five minutes of the 10-minute resting baseline period.

PEP is the interval between electrical stimulation of the ventricles (i.e., electromechanical systole) and the opening of the aortic valve (i.e., left-ventricular ejection) and is measured as the time between the Q-wave in the ECG signal and the B-point in the derived impedance signal, dZ/dt (Sherwood et al., 1990; Vrijkotte, Van Doornen, & De Geus, 2004). PEP is heavily influenced by sympathetic innervation of the heart (Sherwood, Allen, Obrist, & Langer, 1986) and is often used as an index of sympathetic nervous system activation, with shorter PEP values indicating greater sympathetic nervous system activation. Impedence cardiography analysis software (IMP 3.0.12, MindWare Technologies Ltd.) was used to inspect, edit, and summarize cardiac impedance data. The distance in cm between the spot electrode at the base of the neck and the spot electrode at the xiphisternal junction was measured and entered into analysis software for the accurate measurement of cardiac pre-ejection period (PEP).

Impedence cardiography calibration settings included an impedance magnitude (Zo) measured at 0.05 V/Ohm and the derivative (dZ/dt) measured at 0.80 V/Ohm. Q-points were calculated using the minimum value K–R interval method, with K set at 50; B-points were calculated using the percent of dZ/dt time method, with percent set at 55, and stroke volume was calculated using the Kubicek method. The ECG and impedance waves were visually inspected within 60-second analysis epochs. Markers were adjusted as needed to ensure proper placement of the Q-wave and R-wave of the ECG signal, and the B-point (i.e., maximal change in slope), Z-point (i.e., peak of dZ/dt), and X-point (i.e., post-peak trough) on the impedance wave before saving ICG parameters for data analysis.

4.5. *Measures: self-reported self-regulation*

Difficulties in Emotion Regulation Scale (DERS; Gratz & Roemer, 2004**).** The DERS is a 41-item self-report measure of emotion regulation. Items (e.g., *When I'm upset, I have difficulty getting work done*) are rated on a 5-point Likert scale from "Almost Never (0–10%)" to "Almost Always (91–100%)." Cronbach's alpha for the DERS in the current study was 0.93. Given recent examination of the psychometric properties of the scale (Hallion, Steinman, Tolin, & Diefenbach, 2018), we also examine associations with subscales Awareness, Clarity, Goals, Impulse, Non-Acceptance, and Strategies in secondary analyses.

Attentional Control Scale (ACS; Derryberry & Reed, 2002**).** The 20 Likert-item ACS is a self-report measure of perceived attention control abilities, including ability to focus attention (e.g., *When I need to concentrate and solve a problem, I have difficulty focusing my attention*- reverse scored) and shift attention (e.g., *It is easy for me to alternate between different tasks*). Item responses are from 1 (almost never) to 4 (always). Total scores reflect general perceived ability to control attention. Cronbach's alpha in the current sample was 0.82. Secondary analyses with subscales Focusing and Shifting (Judah, Grant, Milla, & Lechner, 2014) were also conducted.

Daily Ratings of Perceived Self-Regulation Difficulties. During a 3-day experience sampling assessment, participants were asked to complete nighttime ratings of difficulties in self-regulation experienced throughout that day. Nine items, rated on a five-point Likert scale ranging from 0 (not at all) to 4 (constantly), were selected from the Behavior Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000) and the Conners Adult ADHD Rating Scales (Conners, Erhardt, & Sparrow, 1996). These items were used to assess subjective difficulties in self-regulation, including emotion regulation (e.g., *Thinking about today only, to what extent did you get upset or angered over little things*) and behavioral regulation (e.g., *Thinking about today only, to what extent did you say or do things without thinking*). Perceived self-regulation difficulties were averaged across nights. Cronbach's alpha was 0.83 for total perceived self-regulation difficulties.

4.6. *Measures: demographic and lifestyle covariates*

Baseline questionnaires included an item for years of education, as well as an item asking for the average number of hours per week of exercise as a general measure of physical activity (converted to minutes for analyses). Body Mass Index (BMI) was obtained through objective measurement of height and weight.

4.7. *Statistical approach*

Direct relations among study variables, were first examined with zero-order correlations. Next, to account for respiration effects on vagal tone, we created a residualized HF-HRV with respiration rate controlled. We then ran a regression model that included the residualized term, as well as respiration rate and amplitude, predicting the EF residual. Next, regression models controlled for and tested interaction effects with age and sex, as well as BMI, physical activity, and education with both EF and resting HF-HRV as the DV. Finally, secondary analyses were conducted to examine associations between resting HF-HRV and EF subscales, as well as subscales on the global measures of emotion regulation and attentional control.

5. Results

5.1. *Descriptive statistics and correlations*

Means, standard deviations, and correlations among main study variables are shown in Table 2. The EF residual was significantly correlated with resting HF-HRV (r = .39). The association was significant for both males and females, rs = .45 and 0.35, respectively, $ps < .05$. The non-EF composite and the WAIS working memory composite were not significantly associated with resting HF-HRV. The EF residual was not significantly associated with resting PEP. These findings support the specificity of the association between EF and resting HF-HRV. Notably, neither resting HF-HRV nor the EF residual score were associated with self-report measures of self-regulation. Because resting heart rate is thought to reflect parasympathetic nervous system activation and should be inversely correlated with resting HF-HRV, we also examined correlations with that variable. Resting heart rate had a significant negative association with resting HF-HRV, $r = -0.61$, $p < .01$, was unrelated to resting PEP, $r = .02$, $p > .10$, and was significantly associated with the EF residual score, $r = -0.27$, $p < .05$.

5.2. *Regression analyses*

Treatment of respiration in measuring heart rate variability

Table 2
Zero-Order Correlations Among Study Variables.

Variable	1	2	3	4	5	6	7
1. EF residual							
2. Resting HF-HRV	.39***						
3. Resting PEP	−.06	.11					
4. DKEFS-Non-EF	−.03	.12	−.04				
5. WAIS-WM	.40***	.14	.05	.19			
6. ACS	−.12	.05	−.04	−.02	−.19		
7. DERS total	−.15	.10	−.03	.16	.08	−.30**	
8. Daily SR ratings	.04	.16	−.05	.04	−.09	−.16	.36**

Note: DKEFS = Delis-Kaplan Executive Function Scales; EF = Executive Functioning; HF-HRV = high frequency-heart rate variability; PEP = pre-ejection period; WAIS = Wechsler Adult Intelligence Scale; WM = working memory; ACS = Attentional Control Scale; DERS = Difficulties in Emotion Regulation Scale; SR = self-regulation
*p < .05.
** p < .01.
*** p < .001.

continues to be a topic of debate. There is evidence that the effects of respiration on parasympathetic indices of HRV when recorded under resting state conditions are minimal and resting state HRV is recorded best under conditions of spontaneous breathing (e.g., Larsen et al., 2010; Bertsch et al., 2012). It is also the case that controlling for respiration when examining HRV indices will remove variability associated with neural control over the heartbeat (see Larsen et al., 2010 for review). Nevertheless, because respiratory parameters can confound associations between HF-HRV and cardiac vagal tone (Grossman & Taylor, 2007), we created a variable using a regression approach to statistically control for respiration rate (Grossman, Karemaker, & Wieling, 1991). That is, a new residual HF-HRV variable, controlling for respiration rate, was created for each participant. This variable was significantly associated with the EF residual, $r = .39$, $p < .001$. We also conducted a regression analysis that examined the association between the residualized HF-HRV variable and EF residual, controlling for respiratory rate and amplitude (the latter as an estimator of tidal volume). In that model, neither respiration rate nor amplitude was a significant predictor of the EF residual, $ps > .10$, whereas the residualized resting HF-HRV variable remained significantly associated with the EF residual, $\beta = .38$, $p < .001$.

Given that both EF and HF-HRV vary with lifestyle and demographic factors, we repeated the regression model with BMI, reported physical activity (minutes per week), and education (years), as well as age and sex in the model. Note that interaction effects, including quadratic terms, were initially tested; none were significant, $ps > .10$. Thus, the trimmed first-order effects models are reported. These regression models were done first with HF-HRV as the outcome variable, then with the EF composite as outcome variable (Table 3). Change in R^2 was calculated using hierarchical regression. In the first model, EF remained a significant predictor and none of the covariates were significantly associated with resting HF-HRV. In the second model, education was a significant predictor of the EF residual, but the association between resting HF-HRV and the EF residual remained significant.

As in the correlation analyses, we tested resting HR in regression models with covariates. The association between resting HR and the EF residual was somewhat diminished ($\beta s = -0.17$ and $-.19$, $ps = .16$ vs. $r = -0.27$), due to the significant association of education with EF, $\beta = -.33$, $p = .03$. As with resting HF-HRV, resting HR was unrelated to any of the covariates, $ps > .45$.

Table 3
Regression models examining the association between EF (residual) and resting HF-HRV, controlling for age, sex, years of education, physical activity (average minutes per week), and BMI.

	β	*t*	p	ΔR^2
IV: Executive Functioning				
DV: Baseline HF-HRV				
Age	−0.13	−1.03	p > 0.05	
Sex	−0.12	−0.877	p > 0.05	
Years of Education	0.04	0.237	p > 0.05	
Physical Activity	0.03	0.228	p > 0.05	
BMI	−0.1	−0.758	p > 0.05	
Executive Functioning	0.33	2.53	p = 0.01	0.1
Total R^2 = 0.15; Adj R^2 = 0.06				
IV: Baseline HF-HRV				
DV: Executive Functioning				
Age	−0.04	−0.34	p > 0.05	
Sex	−0.06	−0.501	p > 0.05	
Years of Education	−0.31	−2.14	p = 0.04	
Physical Activity	−0.05	−0.317	p > 0.05	
BMI	−0.06	−0.451	p > 0.05	
Baseline HF-HRV	0.31	2.53	p = 0.01	0.09
Total R^2 = 0.21; Adj R^2 = 0.13				

5.3. Secondary analyses

HF-HRV associations with DKEFS subtests. For reasons outlined previously, the current study focused on a composite of EF, controlling for lower-order cognitive processes (i.e., EF residual). However, the magnitude of association with DKEFS subtests were examined as comparison to previous studies that have typically focused on individual EF tests. The range of association was $0.05 < rs < 0.36$ across eight subtests (see Table 4). Four subtests were not significantly associated with resting HF-HRV (Trail-Making, Verbal Fluency-Letter, Design Fluency-Switch Dots, Color-Word [Stroop]-Inhibition), $ps > .10$. In summary, the magnitude of association with the EF residual (i.e., the composite after controlling for lower-order processes) was greater than that for all individual subtests, with several subtests showing no association with resting HF-HRV.

HF-HRV and EF associations with DERS subscales. Neither resting HF-HRV nor the EF residual was correlated with any of the DERS subscales $ps > .10$, with the exception of an association between EF and the Clarity subscale, $r = -0.23$, p = .04.

HF-HRV and EF associations with ACS subscales. Neither resting HF-HRV nor the EF residual was correlated with either of the ACS subscales, $ps > .10$.

5.4. Discussion

The current study examined associations between executive functioning (EF) and resting high frequency-heart rate variability (HF-HRV). Using a comprehensive and reliable method to assess EF in a carefully screened, healthy adult sample, a significant association was found with resting HF-HRV.

Current findings are consistent with past research demonstrating that individuals with higher tonic HF-HRV evidence better performance on tests of EF (e.g., Hansen, Johnsen, & Thayer, 2009; Stenfors, Hanson, Theorell, & Osika, 2016; Williams et al., 2016). The associations found in the current study correspond to a “medium” effect size (per Cohen, 1988) and fall in the upper third of the distribution of correlations in psychology research (see Hemphill, 2003), notable given that there is no shared method variance between EF and resting HF-HRV assessment. The effect size of this association in the current study was larger than previously reported in single studies of this association, as well as in meta-analyses of HRV associations with “self-control” (Zahn et al., 2016) and “top-down self-regulation” (Holzman & Bridgett, 2017). The larger effect found in the current study could be attributed to successfully addressing limitations of prior research by a) comprehensive assessment of EF; b) control of lower-order cognitive processes; c) use of individually-administered EF tests and generation of an EF composite to increase reliability; d) focus on frequency characterization of HRV, considered to better reflect parasympathetic functioning (Berntson et al., 1997); and e) examination of a younger, healthy sample. Indeed, examination of individual DKEFS subtests without control of lower-order processes revealed that most associations with HF-HRV were of substantially lower magnitude and, in half the cases, were non-significant. These findings illustrate the vagaries of using single tests of EF. Such an approach is likely to underestimate effect size. For example, had the current study utilized only the Trail Making task (i.e., Trails B) to quantify EF (not uncommon in the literature), the conclusion would have been that resting HF-HRV is unrelated to the construct.

The present findings also suggest a stronger association between EF and autonomic nervous system indices reflecting parasympathetic versus sympathetic activation. This is in contrast to a recent study that reported that resting PEP was independently related to performance on a selective attention task (Giuliano et al., 2018). There are a variety of possible explanations for these divergent findings including many of the same factors we have identified as problematic in the literature more broadly such as use of single behavioral tasks, unknown relationship of the specific task to EF, uncertain reliability of the task, and effects of

Table 4
Zero-order correlations between resting HF-HRV and DKEFS subtests.

Variable	1	2	3	4	5	6	7	8
1. Resting HF-HRV								
2. Trail Making	0.05							
3. Verbal Fluency-Category	0.24*	0.11						
4. Verbal Fluency-Letter	0.16	0.02	0.51***					
5. Design Fluency-Empty dots	0.36**	0.15	0.16	0.22*				
6. Design Fluency-Filled dots	0.31*	0.13	0.26*	0.2	0.77***			
7. Design Fluency-Switch dots	0.23	0.25*	0.13	0.12	0.39***	0.47**		
8. Color-Word [Stroop]- Inhibition	0.22	0.15	0.22*	0.36**	0.12	0.21	0.21	
9. Color-Word [Stroop]-Switching	0.25*	0.18	0.15	0.26*	0.12	0.21	0.34**	0.69***

Note: HF-HRV = high frequency-heart rate variability.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

participant characteristics such as age. However, the present use of validated measures of EF and careful characterization of both the task and participants bolsters the apparent specificity of the EF effects to parasympathetic nervous system activity. Future studies are needed to further explore whether sympathetic nervous system activity is also related to EF.

It is also the case that neither EF nor resting HF-HRV, individual difference factors that have been associated with the higher-order constructs "behavioral self-regulation" and "self-regulatory capacity," respectively, were related to self-reported (i.e., perceived) self-regulatory abilities. These findings are consistent with prior research demonstrating that self-reported cognitive abilities are largely uncorrelated with behavioral performance measures (Williams, Rau et al., 2017). As in past research, self-report measures were significantly intercorrelated, but were unrelated to behavioral performance (EF) or to resting HF-HRV. Current findings suggest that *perceived* self-regulatory abilities should perhaps be considered a different construct than objective measures associated with self-regulation. Furthermore, it is possible that individuals who are high in EF have a different response bias (i.e., a different self-evaluation of one's regulatory ability) than individuals who are low in EF. This is because error and discrepancy monitoring represent key aspects of EF (Suchy, 2015). Thus, individuals with better EF may be more likely to notice self-regulatory failures and thereby evaluate themselves more critically than those with poorer EF. This is a specific variation of the "Dunning-Kruger effect"—that individuals with demonstrably poorer cognitive or intellectual functioning tend to erroneously assess their abilities as greater than they are (Kruger & Dunning, 1999).

The association between these two individual difference factors is consistent with an apparent connection between behavioral and physiological self-regulation. Given that both resting HF-HRV and EF have been associated with a large array of overlapping mental and physical health outcomes, current findings may inform future examination of reciprocal transdiagnostic mechanisms for the development of both psychopathology and chronic illness. For example, resting HF-HRV associations with emotion dysregulation psychopathology (e.g., Beauchaine & Bell, 2019), might be partly attributable to associations with EF. Conversely, EF associations with some health and disease endpoints (e.g., Williams, Tinajero et al., 2017), might be partly attributable to associations with resting HF-HRV. Current findings are consistent with prior studies indicating that interventions focused on one of the indices may have ameliorative changes in the other (e.g., Mather & Thayer, 2018; Sloan et al., 2009). Importantly, however, whereas the association in the current study was significant, it was not of a magnitude suggesting that resting HF-HRV and EF performance fully reflect an identical higher-order construct, in the convergent validity sense. Thus, researchers should exercise caution and avoid language that suggests they are inter-changeable indices of the broader umbrella term "self-regulation."

The stronger association between EF and resting HF-HRV in the current study compared to many prior studies may also reflect the younger, healthier sample. Studies that have examined the association in middle aged or older adult samples have found modest or non-significant associations (e.g., Kimhy et al., 2013). There is evidence that the extent to which HF-HRV predicts amygdala-ventrolateral PFC functional connectivity is substantially greater in younger vs. older adults (Sakaki, 2016). Although indirect, such findings suggest that the EF-HF-HRV associations may diminish with age. Importantly, limitations in the measurement or timing of EF in prior studies examining age effects preclude making strong conclusions about lifespan changes in the relation between EF and resting HF-HRV.

5.5. Conclusions, limitations, and future directions

Strengths of the study include individually administered neuropsychological tests of EF combined into a reliable composite and controlled for lower-order processes, spectral analysis of HRV to better reflect parasympathetic involvement, and daily ratings to supplement questionnaire assessment of self-regulation. The well-characterized younger sample was by design given the focus on individual differences in *vulnerability*, with a priori hypotheses and assessment procedures chosen to measure the individual difference factors of interest reliably. Notably, many of the prior examinations of resting HF-HRV and EF were post-hoc analyses of data collected for other purposes.

Some neurophysiological models suggest that the fidelity of PFC-vagal connectivity may decline with age; thus, the magnitude of EF-resting HF-HRV association is likely to be more modest in older samples. Importantly, declines in resting HF-HRV with age (Tsuji et al., 1996) would also affect the strength of association with EF in older adults. Rather than treating age as a covariate, future research might examine age as a moderator in large samples with a greater age distribution, as well as control for lower-order processes (e.g., processing speed) known to decline with age. The current study sample was largely Caucasian and predominantly female; future research should seek to examine these associations in a more ethnically diverse sample with a more balanced representation of both males and females. Longitudinal studies are needed to examine the stability of executive functioning and resting HF-HRV, as well as reciprocal associations over time.

The methods of the current study correspond to previous suggestions for the assessment of resting HF-HRV as an index of parasympathetic nervous system function (cardiac vagal tone) (Laborde, Mosley, & Thayer, 2017). Although there is evidence of a strong HF-HRV association with vagal activity in animal models (e.g., Kuo, Lai, Huang, & Yang, 2004), some researchers suggest that it is an imperfect estimator of absolute levels of vagal activity in humans, due to residual respiratory activity (Grossman & Kollai, 1993). Recent pharmacological blockade research supports the interpretation of HF-HRV as an indicator of vagal activity in humans (Kromenacker, Sanova, Marcus, Allen, & Lane, 2018); however, this is an ongoing point of investigation.

Although further research is needed, the findings of the current study appear consistent with theoretical models positing an association between prefrontal cortex functioning and parasympathetic nervous system functioning. Whether or not resting HF-HRV partly reflects individual differences in “self-regulatory capacity,” as has been suggested in a growing number of studies, cannot be determined in any single study. Nevertheless, demonstrating an association with performance on tests of EF (i.e., set-maintenance, inhibition, cognitive control, initiation, and generative fluency) contributes to the cumulative science on resting HF-HRV as an individual difference factor associated with self-regulatory behavior. As noted, EF and resting HF-HRV have been linked independently to a long and overlapping list of mental and physical health outcomes. Whereas current findings do not support the supposition that they reflect an identical higher-order construct, the significant association between the two may inform future investigation of transdiagnostic mechanisms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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