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High vagally mediated resting-state heart rate variability is associated with superior action cascading

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ABSTRACT

The neurovisceral integration model suggests that individual differences in heart rate variability (HRV), an index of vagal tone, may relate to prefrontal cortical activity and predict performance on cognitive control tasks. The aim of this study was to further verify this model by investigating the relationship between vagally-mediated resting-state HRV and action cascading, a crucial cognitive control function which refers to the ability to cope with multiple response options when confronted with various task goals. Resting-state HRV and performance on the stop-change paradigm, which provides a relatively well-established diagnostic measure of action cascading and response inhibition, was assessed in 88 healthy volunteers (age range 18–33). Compared to individuals with low resting-state HRV, participants with high resting-state HRV showed enhanced action cascading performance, both when a disruption (stopping) and change towards an alternative response were required simultaneously, and when requirements were cascaded (i.e. when the stopping process had already finished at the time the change was required). Our findings represent an important step towards extending our understanding of the neurovisceral integration model in cognitive control.

1. Introduction

The neurovisceral integration model (Thayer et al., 2009) suggests that individual differences in heart rate variability (HRV) may predict performance on cognitive control tasks. According to this model, vagally-mediated HRV plays a key role in signaling functional activity of the prefrontal cortex, a crucial area that drives cognitive control; the way we control our thoughts and goal-directed behavior (Miller, 2000). HRV is a measure of beat-to-beat temporal fluctuations in the heart rate and has been considered a proxy of parasympathetic control and vagal tone (Berntson et al., 1997). Reduced HRV is an index of poor autonomic nervous system regulation and is linked to increased risk of all-cause mortality (Thayer and Lane, 2007).

In a nutshell, the neurovisceral integration model (Thayer and Lane, 2000; Thayer et al., 2009) suggests that functioning of prefrontal-subcortical inhibitory circuits is critical for self-regulation. These circuits provide inhibitory input to the heart through the vagus nerve (see also Levy, 1971; Benarroch, 1993; Ellis and Thayer, 2010). A number of neuroimaging and pharmacological investigations have provided evidence for an association between inhibitory prefrontal-subcortical circuits and cardiac vagal tone indexed by vagally-mediated resting HRV (Ahern et al., 2001; Lane et al., 2009; for a review, see Thayer et al., 2009). Crucially, a recent meta-analysis (Thayer et al., 2012) has proposed that high resting-state HRV is associated with optimal functioning of prefrontal-subcortical inhibitory circuits that sustain flexible and adaptive responses to environmental demands (Thayer and Lane, 2000; Thayer et al., 2009).

So far, the majority of studies evaluating the neurovisceral integration model investigated the role of vagally-mediated resting HRV in emotion regulation (see Park and Thayer, 2014, for a recent review on the topic). Only few studies have explored, instead, the role of HRV in well-established cognitive control tasks. From these previous studies, the following picture arises: high HRV seems to be related to better cognitive inhibition, mental flexibility, and working memory updating (Hansen, Johnsen, and Thayer, 2003; Stenfors et al., 2016; Jennings et al., 2015; Luque-Casado et al., 2013, 2016). However, it is important to note that in the studies mentioned above, different HRV measures were recorded employing different methods (e.g. during rest, during cognitive activities, and/or during recovery), which makes it difficult to draw strong conclusions based on comparison of these studies. Given that, as proposed by Thayer et al. (2012), high resting-state HRV seems to be associated with optimal functioning of prefrontal-subcortical

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inhibitory circuits, and given our goal to test the neurovisceral integration model (Thayer et al., 2009), we will focus on resting-state HRV in the current study. Specifically, the aim of the present study is to gain a better understanding of the association between vagally-mediated resting-state HRV and improved cognitive control by investigating action cascading. Action cascading is a crucial cognitive control function, which refers to the ability to cope with multiple response options when confronted with various task goals. In order to assess whether high resting-state HRV is associated with an enhanced ability to prioritize and cascade different actions, we employed a stop-change (SC) task introduced by Verbruggen, Schneider, and Logan (2008). In this task, the main goal is to respond to a GO stimulus as fast as possible. Sometimes, a STOP stimulus is presented, which signals participants to stop the ongoing action. The STOP stimulus is followed by a CHANGE stimulus that informs participants to shift to another action. The time available to prepare for the execution of the change response (i.e. the delay between the STOP and CHANGE stimuli) is manipulated such that the interval between the STOP and the CHANGE stimuli (stop-change delay; SCD) can be 0 ms (i.e., SCD 0), that is, the two stimuli occur simultaneously, or it can be 300 ms (i.e., SCD 300), that is, they occur with a short delay, see Fig. 1. Responses on SC trials rely on the ability (a) to activate different task goals, and to cascade and prioritize different actions; (b) to succeed in inhibiting an ongoing response, and (c) to rapidly switch to a different response (Beste & Saft, 2015; Stock et al., 2014a; Stock et al., 2014b). Accordingly, reaction times (RTs) on SC trials can be taken to reflect the efficiency of action cascading, with lower RTs reflecting more efficient action cascading and selection.

Following previous studies, we employed the root of mean squared successive differences in heart-beat-intervals (RMSSD) measured during rest as a reliable index of resting-state vagally-mediated HRV (DeGiorgio et al., 2010; Koenig et al., 2016; Sperling et al., 2010). In sum, based on the neurovisceral integration model (Thayer et al., 2009), which proposes that high resting-state HRV is associated with optimal functioning of prefrontal-subcortical inhibitory circuits, we expected individuals associated with high resting-state RMSSD values (superior vagus-mediated HRV) to outperform individuals associated with low resting-state RMSSD (poor vagus-mediated HRV) in action cascading processes. That is, we expected them to show faster RTs on the SC trials both when an interruption (stopping) and a change toward an alternative response are required simultaneously (SCD0), and when the change to another response is required when the stopping process has already finished (SCD300).

2. Methods

2.1. Participants

Eighty-eight Leiden University undergraduate students (50 men, 38 women; mean age = 21.20 years, range 18–33; mean body mass index (BMI) = 22.17, range 18–30, mean vagally-mediated HRV = 39.75 ms, range 15–83) participated in the study. Participants were recruited via an on-line recruiting system and were offered partial course credit for participating in a study on the relationship between HRV and cognitive processes. Participants were screened individually using the Mini International Neuropsychiatric Interview (M.I.N.I.; Sheehan et al., 1998). The M.I.N.I. is a well-established brief diagnostic tool in clinical and stress research that screens for several psychiatric disorders and drug use, and it is often used in clinical and pharmacological research (Colzato, van den Wildenberg, and Hommel, 2013; Colzato, Pratt, and Hommel, 2010). Based on a median split of resting-state HRV (=34.96 ms), we created the two groups of 44 low resting-state HRV and 44 high resting-state HRV participants.

Demographic statistics are provided in Table 1. Written informed consent was obtained from all participants. The experiment conformed to the ethical standards of the Declaration of Helsinki and the protocol was approved by the local ethics committee (Leiden University, Institute for Psychological Research). Written informed consent was obtained from all participants.

2.2. Procedure

All participants were tested individually. Upon arrival, participants read and signed the informed consent. Subsequently, participants were weighed and their BMI was measured using an OMRON Body Composition Scale Karada Scan. Next, participants completed a visual analogue scale (range of scores from 0 to 100) that measured the subjective self-reported current level of anxiety, nervousness, insecurity and stress. Following this, participants were asked to remain seated and try to relax for 5 min, after which their HRV was recorded for 5 min. During this measuring period, participants were not instructed about breathing, but instead were breathing spontaneously. It is known that respiration rate does not modulate HRV in resting state measurements (Denver, Reed, and Porges, 2007). After that, participants performed the stop-change paradigm (40 min).

2.2.1. Heart rate variability recordings

Inter-beat intervals (IBI) were measured for 5 min using a Polar H7 heart rate monitoring system (Polar Electro, Kempele, Finland), which wirelessly receives HR data from a chest strap worn by the participants. Data were recorded with the Elite HRV Smart Phone Application (https://elitehrv.com/). Elite HRV automatically calculates the following values to asses HRV: average heart rate as measured in beats per minute (BPM), root mean square of the successive differences (RMSSD), standard deviation of the NN (R-R) intervals (SDNN), the number of successive NN (R-R) intervals that differ by more than 50 ms (NN50), and the proportion of NN50 divided by the total number of NN (R-R) intervals (PNN50, see Weippert et al., 2010). Given that we were mainly interested in vagally-mediated HRV, we focused on RMSSD (DeGiorgio et al., 2010; Koenig et al., 2016; Sperling et al., 2010). The validity of Polar monitors to measure inter-beat intervals (IBI) has been confirmed by Weippert et al. (2010), who measured IBI using a Polar monitor and an electrocardiogram simultaneously. Intra-class correlation coefficients and the Bland–Altman limits of agreement method revealed excellent agreement between the Polar monitor and ECG.

2.2.2. Stop-change paradigm

The experiment was controlled by an Asus laptop running on an Intel Core i3-3217U processor, attached to a LG Flatron 776FM 16 in. monitor (refresh rate of 60 Hz). Stimulus presentation and data collection were controlled using Presentation software system (Neurobehavioral Systems, Inc., Berkeley, CA). The SC paradigm was adapted from Steenbergen et al. (2015a, 2015b) see Fig. 1. Responses were executed via button-presses using the number row of a QWERTY computer keyboard. Throughout the task, the response buttons were marked with yellow stickers. All visual stimuli were presented in white on a black background.

Each trial started with the presentation of four vertically–aligned, unfilled circles (diameter 7 mm) and three horizontal reference lines that separated them (line thickness 1 mm, width 13 mm), embedded in a 55 × 16 mm rectangle presented in the center of the screen. After 250 ms, one of the circle was filled white (GO stimulus). In the GO condition (67% of the trials), participants were to indicate the position (above vs. below) of the white circle relative to the middle reference line. Specifically, participants were instructed to press the “7” key (for below) and the “8” key (for above) with the index and middle finger of their right hand, respectively. Stimuli were shown until response or until 2500 ms after stimulus onset. Participants were instructed to emphasize both accuracy and speed. When RTs were longer than 1000 ms, the word “Quicker” was presented above the rectangle until the participant responded.

In the SC conditions, which corresponded to the remaining 33% of the trials, the presentation of the white GO stimulus was followed by a