

The link between resting heart rate variability and affective flexibility

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HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Abstract

The neurovisceral integration model aims to account for the complex interplay between physiological, cognitive, and emotion regulation processes through their support by common cortico-subcortical neural circuits. According to the model, vagally mediated heart rate variability (HRV) serves as a peripheral index of the functioning of these circuits, with higher levels of resting HRV reflecting more optimal functioning, to support goal-directed behaviour and adaptability to environmental demands. Although increased cognitive flexibility has been related to higher resting HRV, this has not been assessed in the context of emotional information to examine the interplay between cognition and emotion. Therefore, we investigated ($n = 109$) the relationship between resting HRV and performance on a task-switching paradigm in which participants shift attention between affective and non-affective aspects of emotional material. Resting HRV was not associated with flexibility in processing of positive material, but more efficient shifting of attention (greater flexibility) from affective to non-affective aspects of negative information was related to lower resting HRV. The avoidance theory of worry and anxiety, as well as empirical evidence links anxiety to attentional avoidance of negative information. Our findings therefore support the neurovisceral integration model such that when greater flexibility can facilitate attentional avoidance of negative information—as seen in anxiety—it is related to lower resting HRV.

Keywords: heart rate variability, RMSSD, vagal tone, cognitive flexibility, affective flexibility

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

The neurovisceral integration model proposes that physiological, emotion, and cognitive regulation processes are related to each other in the service of goal-directed behaviour and adaptability to changing environmental demands (Thayer, Hansen, Saus-Rose, & Johnsen, 2009; Thayer & Lane, 2000). The interplay between these factors can contribute to individual differences in (mental) health and disease. The model summarizes the relationship between the central nervous system (CNS) and the autonomous nervous system (ANS), and puts forward a common cortico-subcortical neural circuit that serves as the structural link between these regulation processes. A network of neural structures (for overviews see Thayer, Åhs, Fredrikson, Sollers, & Wager, 2012; Thayer et al., 2009; Thayer & Lane, 2000) consisting amongst others of prefrontal areas including ventromedial prefrontal cortex and anterior cingulate cortex, and subcortical areas such as the hypothalamus and amygdala, are together called the central autonomic network. This central autonomic network regulates the ANS through sympathetic and parasympathetic (vagal nerve) branches that innervate the heart (Appelhans & Luecken, 2006; Benarroch, 1993). It is the interaction between the sympathetic and parasympathetic subsystems of the ANS that has a prominent influence on cardiac activity and regulates the time between consecutive heartbeats. This dynamic balance between the sympathetic and parasympathetic branch allows for flexible control over the response of the body (e.g. heart) to a range of external and internal stimuli. An increase in heart rate could result from activation of sympathetic fibers or decreased parasympathetic inhibition (vagal withdrawal). The parasympathetic system is more dominant in maintaining resting heart rate. Whereas sympathetic influence on heart rate unfolds in a relatively slower manner, parasympathetic regulation of the heart is much faster, allowing for momentary modulation of cardiac activity (Pumprla, Howorka, Groves, Chester, & Nolan, 2002). Heart rate variability (HRV) is the variation in time intervals between heart beats and provides an index of this parasympathetic influence on the heart (Laborde, Mosley, & Thayer, 2017). As the

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

vagus nerve is the primary parasympathetic nerve (Brodal, 2010), when we refer to HRV, we always refer to vagally mediated HRV.

The central autonomic network regulates this autonomic influence on heart rate (Benarroch, 1993) and its output is thus directly linked to HRV (Thayer et al., 2009; Thayer & Lane, 2000). Thayer and colleagues (2012, 2009; 2000) have reported considerable structural overlap of the central autonomic network and neural circuits supporting cognitive and emotion regulation processes that allow for goal-directed behaviour and flexible adaptation to changing environmental demands. The neurovisceral integration model postulates that HRV serves as a peripheral index of the functional capacity of these cortico-subcortical neural circuits and higher levels of resting HRV (measured when individuals are doing nothing) are believed to reflect more optimal functioning of this network (Thayer et al., 2012). In support of this idea they show that cognitive, emotion, and physiological regulation are associated with cardiac vagal tone as measured by resting HRV (Thayer et al., 2009; Thayer & Lane, 2000).

The same neural circuits that have been linked to HRV (Thayer et al., 2012, 2009; Thayer & Lane, 2000) are indeed also underlying regulation of emotion, and dysfunctions in parts of this circuitry have been associated with psychopathology (Davidson, Pizzagalli, Nitschke, & Putnam, 2002). Previous work has shown a relationship between higher resting HRV and better emotion regulation (Appelhans & Luecken, 2006; Balzarotti, Biassoni, Colombo, & Ciceri, 2017; Ruiz-Padial, Sollers, Vila, & Thayer, 2003; Thayer & Brosschot, 2005). On the other hand, disorders of emotion dysregulation, such as anxiety, are proposed to be characterized by a rigid coupling of the CNS-ANS system, reflected by elevated sympathetic activity and reduced parasympathetic (vagal) control as measured by vagally mediated HRV (for review see Friedman, 2007). Anxiety indeed seems to be characterized by the inability to inhibit responses to threat that have amongst others cognitive, behavioural (e.g. avoidance), affective (e.g. fear) and autonomic (e.g. HR

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

increase) components (Friedman, 2007). Several studies find that anxiety, both in non-pathological and pathological form, is associated with reduced resting HRV levels (Friedman, 2007). Worry, which is a form of perseverative thinking and a core cognitive feature of generalized anxiety disorder (GAD), has also shown to lower phasic HRV levels in both GAD patients and healthy controls (Thayer, Friedman, & Borkovec, 1996). Similarly, it has been shown that lower levels of resting HRV are correlated with maladaptive forms of perseverative thinking (i.e. brooding and depressive rumination) and it has been demonstrated that this thinking style partially mediates the relationship between lower resting HRV and anxiety (Williams et al., 2017).

The neurovisceral integration model aims to account for the complex interaction between physiological, affective and cognitive processes. Besides the link between HRV and emotion (dys-)regulation, research has therefore also focused on the role of individual differences in resting HRV and executive function. Executive functions are a set of cognitive control processes consisting of inhibition of prepotent responses, mental set shifting (i.e. cognitive flexibility), and updating and monitoring of information in working memory (Miyake et al., 2000). These processes allow flexible adaptation of behaviour and cognition in line with one's goals and changing environmental demands. Cognitive flexibility has therefore been proposed as one of the cognitive mechanisms underlying effective emotion regulation (Genet & Siemer, 2011; Ochsner & Gross, 2007). On the other hand, deficits in cognitive flexibility have been associated with trait anxiety and GAD which are characterized by emotion dysregulation (Ansari, Derakshan, & Richards, 2008; Kim et al., 2019; Lee & Orsillo, 2014), although this hasn't always been replicated (Han et al., 2016). Executive functions rely on a prefrontal-parietal network (Niendam et al., 2012) that partially overlaps with the neural circuits associated with HRV and emotion

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

processing (Thayer et al., 2012), and this common cortico-subcortical neural network may thus serve as the link between cognitive, emotional and physiological processes.

Previous research has linked higher levels of resting HRV to better performance on tasks of monitoring and updating working memory, attention control and response inhibition (Thayer et al., 2009 for a review; Zahn et al., 2016 for a meta-analysis). Although most research has investigated the link between HRV and executive functions of inhibition and updating and monitoring working memory, few studies have measured cognitive flexibility (i.e. mental set shifting). In a study in a sample of patients with panic disorder, it has been shown that higher resting HRV is associated with better performance on the Wisconsin Card Sorting Test, a measure of set shifting that also requires working memory (Hovland et al., 2012). A more recent study in an unselected sample used a task-switching paradigm in which cognitive flexibility is reflected by switch costs: an increase in reaction time (RT) on task-switching trials as compared to task-repetition trials. The authors observed a relationship between higher levels of resting HRV and smaller switch costs (i.e. greater cognitive flexibility) (Colzato, Jongkees, de Wit, van der Molen, & Steenbergen, 2018).

The links across vagally mediated HRV, cognitive flexibility and emotion (dys)regulation fit well with the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000). However, previous research has typically measured cognitive flexibility with tasks using non-affective stimuli, but it may be particularly interesting to assess cognitive flexibility in the context of affective information and how this is related to HRV. Especially as disorders of emotion dysregulation, such as depression and anxiety, are associated with a biased processing of affective information (for reviews see Cisler & Koster, 2010; Joormann & Stanton, 2016). This allows to really examine the interplay between physiological regulation, emotion, and cognitive control.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Cognitive flexibility in the context of affective information is here referred to as affective flexibility and has been measured with a task switching paradigm where individuals have to sort positive and negative images according to an affective rule (i.e. valence of the picture) or a non-affective rule (i.e. the number of people depicted) (Genet, Malooly, & Siemer, 2013; Malooly, Genet, & Siemer, 2013). More flexibility (i.e. lower switch costs) when shifting attention towards non-affective aspects of negative information and towards affective aspects of positive information has shown to predict more effective reappraisal when instructed to use this emotion regulation strategy (Malooly et al., 2013). In another study a relationship was found between less flexibility when shifting attention towards non-affective aspects of negative information and rumination (Genet et al., 2013). Interestingly, less flexibility when shifting attention towards non-affective aspects of positive information was associated with lower rumination (Genet et al., 2013), highlighting that more flexibility is not adaptive per se and may depend on the context.

Recent unpublished data has also shown that when assessing cognitive flexibility in the context of affective information, more flexibility is not necessarily more adaptive. Whilst more flexibility when shifting attention from non-affective towards affective aspects of positive information was associated with reductions in anxiety across seven weeks, more flexibility when shifting attention towards non-affective aspects of negative information was associated with greater increases in anxiety and worry over time (Twivy, Grol, & Fox, 2019 unpublished manuscript). Although this latter finding seems to contradict previous work on attention facilitation to negative information in anxiety, it is actually consistent with findings of a relationship between anxiety and attentional avoidance of negative stimuli at relatively longer presentation times (Cisler & Koster, 2010). Such attentional avoidance is believed to reflect a strategic process underlying emotion regulation goals (Cisler & Koster, 2010), but it actually leads to the maintenance of anxiety. The model of avoidance in anxiety and worry (Borkovec,

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Alcaine, & Behar, 2004) proposes that worry functions as a cognitive avoidance response to (perceived) future threats. It functions as a cognitive attempt to generate ways to anticipate or prevent bad things from happening, and by shifting attention to worrisome thinking when threatening information is detected, a suppression of somatic arousal occurs. The cognitive avoidance response is therefore negatively reinforced, but it precludes emotion processing of the fear-related information which is necessary for extinction of anxiety responses, leading to a maintenance of worry and anxiety (Borkovec et al., 2004). In support of this, a recent study in children (Lester, Lisk, Carr, Patrick, & Eley, 2019) comparing ‘toward threat’ vs. ‘avoidance of threat’ attention training, found that a larger change in attention bias toward threat (but not away from threat) predicted a greater reduction in anxiety across time. The authors argued that attention bias to threat can facilitate learning that negative information does not always result in an aversive outcome (in line with exposure therapy).

It thus seems that affective information can create a ‘context’ in which more cognitive flexibility, in terms of mental set shifting, is not necessarily more adaptive. In keeping with the neurovisceral integration model’s aim to account for the complex interaction between physiological, affective and cognitive processes (Thayer et al., 2009; Thayer & Lane, 2000), we therefore aimed to investigate the association between resting HRV and cognitive flexibility in the context of affective information. We measured affective flexibility with a task switching paradigm (Malooly et al., 2013) and used the time-domain based root mean square successive difference in beat-to-beat intervals (RMSSD) as our measure of resting state HRV. The RMSSD and the frequency-domain based measure of high-frequency changes in heart beat (HF-HRV) are often highly correlated and both are reliable measures of vagally mediated HRV, but the RMSSD is relatively free of respiratory influences as compared to HF-HRV (Laborde et al., 2017).

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Previous research has associated more efficient shifting (i.e. greater flexibility) from non-affective aspects towards affective aspects of positive information with greater reappraisal efficacy (Malooly et al., 2013) and reductions in anxiety over time (Twivy et al., 2019 unpublished manuscript). Research on resting HRV has associated anxiety with reduced resting HRV (Friedman, 2007), whereas individuals with greater emotion regulation ability have shown higher levels of resting HRV (Appelhans & Luecken, 2006; Thayer & Brosschot, 2005). Bringing these previous findings together, we expected greater flexibility (i.e. lower RT switch costs) when shifting attention from non-affective towards affective aspects of positive information to be associated with higher resting HRV. In contrast, more efficient shifting of attention from affective to non-affective aspects of negative information, possibly facilitating avoidance of affective aspects of negative information, has been associated with greater increases in anxiety over time (Twivy et al., 2019 unpublished manuscript). Based on these findings and models of attentional avoidance of threat in anxiety and worry (Borkovec et al., 2004; Cisler & Koster, 2010), we therefore expected more efficient (i.e. lower RT switch costs) shifting of attention from affective to non-affective aspects of negative information to be associated with lower resting HRV. Previous findings with the affective flexibility task and recent findings associating resting HRV with increased cognitive flexibility (Colzato et al., 2018) are all based on switch costs in RT and no effects were found with switch costs in accuracy. Our hypotheses are therefore focused on switch costs in RT. Given that HRV has been shown to be modulated by age (Umetani, Singer, McCraty, & Atkinson, 1998), gender (Sztajzel, Jung, & Bayes de Luna, 2008; Umetani et al., 1998), anxiety (Friedman, 2007), depression (Kemp et al., 2010), stress (Dishman et al., 2000), and heart rate (Gašior, Sacha, Jeleń, Zieliński, & Przybylski, 2016; Monfredi et al., 2014), we examined the relationship of these variables with HRV in the current study. We controlled for those variables that significantly correlated with resting HRV.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Method

Participants

Hundred-twenty participants were recruited by convenience sampling.¹ Beat-to-beat heart rate recordings of 10 participants were very noisy and this data was therefore excluded from further analyses. Additionally, one participant was excluded from analysis because the percentage of errors in the switching task was more than 3SDs from the sample mean. The final sample therefore consisted of 83 females and 26 males aged between 18-53 years old ($M = 23.19$, $SD = 6.26$). Exclusion criteria were a current or history of cardiovascular disease, seeking help or being in treatment for psychological/psychiatric complaints in the past six months, and use of psychoactive medication or medication that influences cardiovascular activity. The majority of participants in the sample were university students. Participants were paid for their participation. This study was approved by the Medical Ethics Committee at the Ghent University Hospital (reference: EC/2018/1505).

Material

Questionnaires. Trait anxiety was measured using the trait component of the State-Trait Anxiety Inventory (STAI-T; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983; Van der Ploeg, Defares, & Spielberger, 2000). Participants are asked to rate how they generally feel on a 4-point scale from 1 (almost never) to 4 (almost always). A total score is obtained between 20 and 80. In the present study, the STAI-T had high internal consistency ($\alpha = 0.91$).

The Beck Depression Inventory (BDI; Beck, Steer, & Brown, 1996; Van der Does, 2002) was used to measure presence and severity of depressive symptoms during the past two weeks.

¹ This data is part of a larger study on the link between affective flexibility and stress reactivity for which an a-priori power analysis was done. For the current analysis, assuming a medium effect size, alpha level of 0.05 and power of 0.80, the necessary sample size based on the R^2 increase when adding switch costs to the model is 85 participants.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Participants rate items on a 0-3 scale. A total score is obtained between 0 and 63. In the present study, the BDI had high internal consistency ($\alpha = 0.91$).

We measured mood state with visual analogue scales (0 to 10 cm, resulting in a 0-100 scale) measuring how happy, sad, aroused, angry, and tense participants were feeling “at this moment”. We measured how happy and sad participants were feeling on a scale from “neutral” to “as happy/sad as I can imagine”, and we measured arousal on a scale from “calm” to “aroused”. Anger and tenseness were measured on a scale from “not at all” to “as angry/tense as I can imagine”.

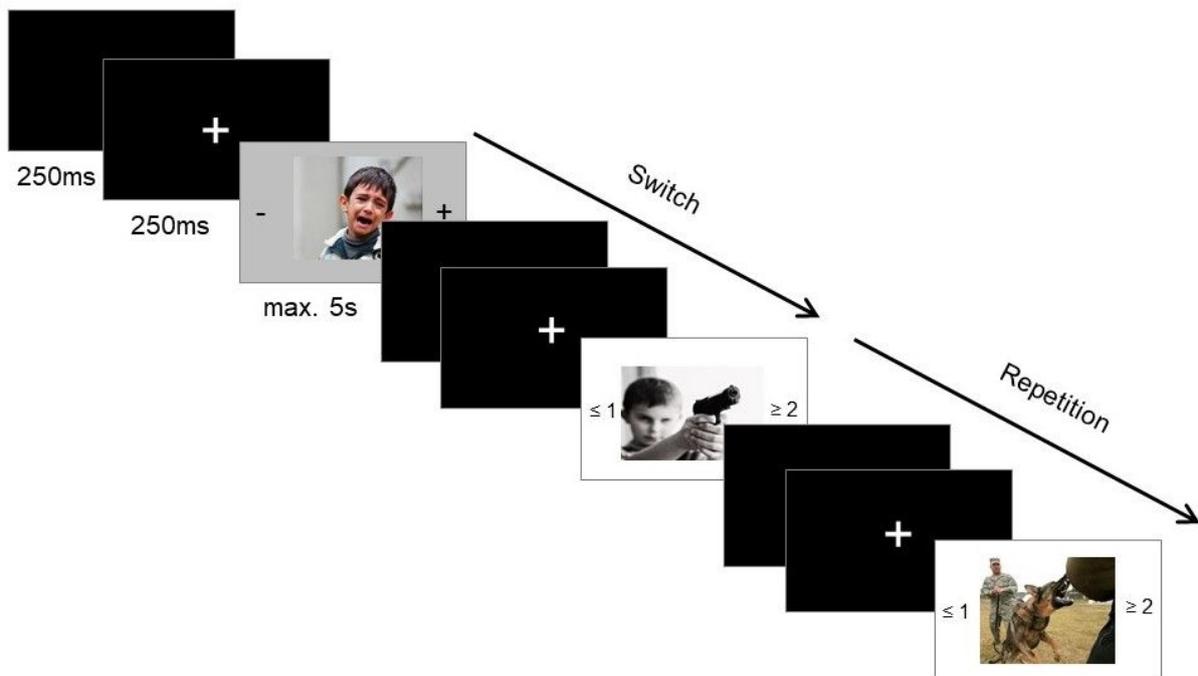


Figure 1: Example of a trial sequence from the task switching paradigm, with a non-affective negative switch trial. The images displayed are for illustrative purposes and are not part of the International Affective Picture System.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Affective flexibility. Affective flexibility was measured using a task switching paradigm based on Malooly et al. (2013). In this task participants have to sort emotional images according to an affective task rule or a non-affective task rule. For the affective task rule participants are instructed to sort the images according to whether the depicted scene is positive or negative. For the non-affective task rule participants have to indicate whether one or no person (≤ 1) is depicted versus two or more (≥ 2) depicted people. Even if only part of a person is depicted this counts as well. Images were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). Forty images were selected for each of the following categories: positive with one or fewer people, positive with two or more people, negative with one or fewer people and negative with two or more people (i.e. 160 images in total). Positive and negative images differed in valence ratings but were balanced in terms of arousal ratings. An additional twenty images were used in the practice blocks.

Each trial started with a black blank screen (250ms), followed by the presentation of a central fixation cross (250ms). See figure 1 for an example trial sequence. Next an emotional image was presented in the centre and cues indicating the relevant task rule appeared on either side of the image: “+” and “-” for the affective task rule and “ ≤ 1 ” or “ ≥ 2 ” for the non-affective task rule. This was presented until the participant responded or for 5000ms, whichever was sooner. The background colour (white or grey) of the screen during presentation of the emotional image and cues also indicated the sorting rule. Participants had to respond by pressing one of two adjacent keys on the keyboard (N and M labelled as “L” and “R”). Instructions told participants to work quickly but try to be as accurate as possible.

The task started with two practice blocks each consisting of 10 trials, in which participants had to first apply the affective rule only, followed by the second block using the non-affective rule only. The test phase consisted of two 160-trial blocks with a break in between. Trials were

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

presented in a pseudorandom order (Malooly et al., 2013). There were eight versions of the task, counterbalancing different combinations of cue to key mappings and rule (affective/non-affective) to background colour (grey/white) mappings.

Calculation of switch costs.² The difference between mean RT on switch trials and repetition trials is termed the switch cost. Four different types of switch costs were calculated following Malooly et al. (2013): non-affective negative switch costs, affective negative switch costs, non-affective positive switch costs, and affective positive switch costs. Mean RT on repetition trials were subtracted from mean RT on switch trials. For example, affective positive switch costs were calculated by subtracting the mean RT on trials involving a repetition of the affective task rule in the presence of positive images, from the mean RT on trials involving a switch away from processing the non-affective aspects towards the affective aspects in the presence of positive images. Negative non-affective switch costs were calculated by subtracting the mean RT on trials involving a repetition of the non-affective task rule in the context of negative images, from the mean RT on trials involving a switch from the affective rule towards the non-affective rule in the presence of negative images. Larger switch costs thus reflect poorer flexibility.

Heart rate variability. Beat-to-beat heart rate was recorded continuously throughout the baseline phase (10min) and the rest of the experiment using a telemetric heartbeat monitor (Polar

² Previous studies have used slightly different ways to calculate the switch costs. Genet and colleagues (2013) calculated non-affective switch costs by subtracting RTs on trials in which the *affective rule was repeated* from RTs on trials in which the task switched from the affective rule to the non-affective rule. Affective switch costs were calculated in an analogous manner. On the other hand, in the paper of Malooly et al. (2013) non-affective switch costs were calculated by subtracting RTs on trials in which the *non-affective rule was repeated* from RTs on trials in which the task switched from the affective rule to the non-affective rule. We use the same method as Malooly et al. (2013) to compare performance on trials where the same task rule has to be performed and which are either preceded by the same task rule (i.e. repetition) or by the other rule (i.e. switch). Otherwise switch costs reflect both the cost in performance when the task rule is switched vs. repeated and a performance difference because trials are compared in which different tasks have to be performed.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

V800; Polar Electro Oy, Kempele, Finland), which wirelessly received data from the chest strap worn by participants. Heart rate and inter-beat interval sequences (i.e. RR intervals) were extracted and further analyzed with Kubios HRV Standard software 3.1.0 (Biosignal Analysis and Medical Imaging Group, n.d.; Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2014). RR interval series were visually inspected for artefacts and corrected using Kubios artefact correction which replaces detected artefact beats using cubic spline interpolation. We used time-domain based RMSSD as our measure of vagally mediated HRV. To test the hypothesis of the current study we used RMSSD based on the 10min baseline phase, corresponding to resting HRV. Resting RMSSD ($M = 42.53$, $SD = 21.13$) and resting HF-HRV (ms^2 , 0.15-0.40Hz) ($M = 1048$, $SD = 1094$) were highly correlated (Spearman $r = 0.95$, $p < .001$), thus only RMSSD was used to assess the associations with affective flexibility. The RMSSD reflects vagally mediated HRV and is relatively free of respiratory influences as compared to high frequency parameters (Laborde et al., 2017).

Procedure

Informed consent was obtained at the start of the session. After checking the exclusion criteria, the telemetric heartbeat monitor was put on and beat-to-beat heart rate registration continued throughout the rest of the experiment.³ Participants then completed the self-report questionnaires (STAI-T and BDI), followed by the affective flexibility switching task. After the computer task we measured the 10-min heart rate baseline period in which participants were asked to sit quietly and to relax. At the end of this baseline period we measured mood state with

³ This study was part of a larger study in which we also measured trait resilience and emotion regulation with self-report questionnaires, and induced stress using a procedure based on the Trier Social Stress Test to measure stress reactivity. However, these measures will not be used to test the hypotheses of the current study.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

the VAS scales. Upon completion of the experiment participants were debriefed about the nature of the study.

Results

We used R (R Core Team, 2019) for all analyses. Specifically we used the R packages tidyverse (Wickham, 2017), psych (Revelle, 2018), and pastecs (Grosjean & Ibanez, 2018) for data manipulation, exploration and descriptive statistics. We used the package Hmisc (Harrell Jr, 2019) to calculate correlations. For the linear regression analysis we used the packages stats (R Core Team, 2019), lmSupport (Curtin, 2018), and QuantPsyc (Fletcher, 2012). Finally, we used RMarkdown (Allaire et al., 2019), papaja (Aust & Barth, 2018), knitr (Xie, 2019), qwraps2 (DeWitt, 2019), and kableExtra (Zhu, 2019) for the reporting and creation of the manuscript.

Preliminary Analysis

Control variables. Variables such as age, gender, average heart rate per minute (BPM), levels of anxiety, depression and mood have been shown to affect resting HRV and we therefore may want to control for these variables in further analyses. We first calculated Spearman correlations (some variables were not normally distributed) to test whether these variables were indeed related to resting HRV in our sample (see Table 1). Based on these correlations we decided to control for BPM in further analyses. An independent t-test to check whether gender influenced HRV showed no significant effect, $t(42.48) = -0.21, p = .833$.

Table 1

Correlations

	HRV	BPM	Age	STAI	BDI	Happiness	Sadness	Arousal	Anger
HRV									
BPM	-0.56***								
Age	-0.14	-0.25**							
STAI	-0.03	-0.02	-0.06						
BDI	0.06	-0.12	-0.18	0.77***					
Happiness	-0.11	0.02	0.01	-0.23*	-0.22*				
Sadness	-0.04	-0.08	-0.02	0.38***	0.32***	0.15			
Arousal	-0.01	0.03	-0.10	0.22*	0.15	0.23*	0.50***		
Anger	-0.14	-0.04	0.04	0.24*	0.15	0.08	0.69***	0.44***	
Tension	0.01	0.03	-0.08	0.32***	0.28**	<0.01	0.48***	0.59***	0.37***

* $p < .05$; ** $p < .01$; *** $p < .001$. HRV = RMSSD heart rate variability index; BPM = average heart rate per minute; STAI = trait anxiety; BDI = depressive symptoms

Affective flexibility data preparation. Practice trials and the first trial of each test block in the affective flexibility task were excluded from analysis. In line with previous studies, we also only included trials that were preceded by a correct trial (Demanet, Liefoghe, & Verbruggen, 2011; Mocan, Stanciu, & Visu-Petra, 2014), because of post-error slowing and if the preceding trial was incorrect it is ambiguous whether the current trial is a repetition or switch from the participant's perspective. To calculate accuracy we thus divided the number of correct trials that were preceded by a correct response by the total number of trials (correct and incorrect) that were preceded by a correct response. One participant was excluded from further analysis because the percentage of errors was more than 3SDs from the sample mean. Only correct trials that were also preceded by a correct response were included in the calculation of mean RT, this resulted in an average deletion of 11.29% of trials for each participant. To reduce the influence of outlying RTs, we replaced RT values 2.5SD above and below the mean RT within each participant and specific trial type by these upper and lower cut-off values, in line with previous studies (Genet et al., 2013; Greenwald, Nosek, & Banaji, 2003; Malooly et al., 2013).

We used paired t-tests on RT on all repetition and switch trials, to confirm the presence of switch costs. RTs on repetition trials ($M = 1256$, $SD = 251.57$) were significantly lower than RTs on switch trials ($M = 1389$, $SD = 278.33$), $t(108) = -17.59$, $p < .001$. We then calculated non-affective negative switch costs, affective negative switch costs, non-affective positive switch costs and affective positive switch costs.

Descriptive Statistics

Mean and standard deviations for measures of trait anxiety, depressive symptoms, self-report measures of emotion and arousal, resting heart rate, resting heart rate variability and switch costs from the affective flexibility task are shown in Table 2.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

Table 2

Descriptive Statistics

	Data (N = 109)
Trait anxiety (STAI)	38.30 (8.43)
Depressive symptoms (BDI)	7.38 (7.47)
Happiness	49.00 (26.00)
Sadness	7.65 (10.63)
Arousal	17.96 (19.08)
Anger	2.81 (5.12)
Tension	13.52 (15.94)
Resting HR	75.17 (8.94)
Resting RMSSD	42.53 (21.13)
Affective negative switch costs (ms)	189.38 (203.72)
Non-affective negative switch costs (ms)	77.17 (203.93)
Affective positive switch costs (ms)	119.02 (165.98)
Non-affective positive switch costs (ms)	184.61 (165.74)

Mean (Standard deviation)

Link between HRV and Affective Flexibility

We performed a hierarchical linear regression analysis with resting RMSSD as dependent variable. In a first step we entered resting heart rate (BPM) to the model to control for the average heart rate per minute. In the second step we entered the four types of switch costs: non-affective negative, affective negative, non-affective positive, and affective positive switch costs.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

The model with just BPM was significant, $F(1, 106) = 53.34, p < .001, \text{adj. } R^2 = 0.33$. Adding the four switch costs to the model near significantly improved fit, $F(4,102) = 2.35, p = .059, \Delta R^2 = 0.06$.⁴ BPM was negatively related to RMSSD with higher BPM related to lower HRV, $\beta = -0.59, t = -7.47, p < .001$. Non-affective negative switch costs were positively related to RMSSD, $\beta = 0.18, t = 2.20, p = .030$. Lower non-affective negative switch costs, that is, more efficient switching towards non-affective aspects of negative information was thus related to lower RMSSD. Neither affective negative ($\beta < 0.001$), non-affective positive ($\beta = 0.12$), nor affective positive switch costs ($\beta = 0.09$) were significant predictors of RMSSD, all $ps > .10$. See figure 2 for the partial correlation between RMSSD and non-affective negative switch costs, controlling for BPM and other switch costs (negative affective switch costs, positive non-affective switch costs, positive affective switch costs). Additional analyses with switch costs calculated as a percentage change from the non-switch baseline are reported in supplemental material.

⁴ Results are reported after exclusion of one outlier based on standardized residuals. With this case, adding switch costs to the model near significantly improved fit, $F(4,103) = 2.16, p = .078, \Delta R^2 = 0.05$. The effect of non-affective negative switch costs was similar, $\beta = 0.19, t = 2.30, p = .023$. When only adding non-affective negative switch costs to the model with BMP, there is a significant improvement of fit, $F(1,105) = 5.98, p = .016, \Delta R^2 = 0.04$. The effect of non-affective negative switch costs was similar, $\beta = 0.19$. Running the analysis with HF-HRV, after transformation to its natural logarithm, resulted in similar findings.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

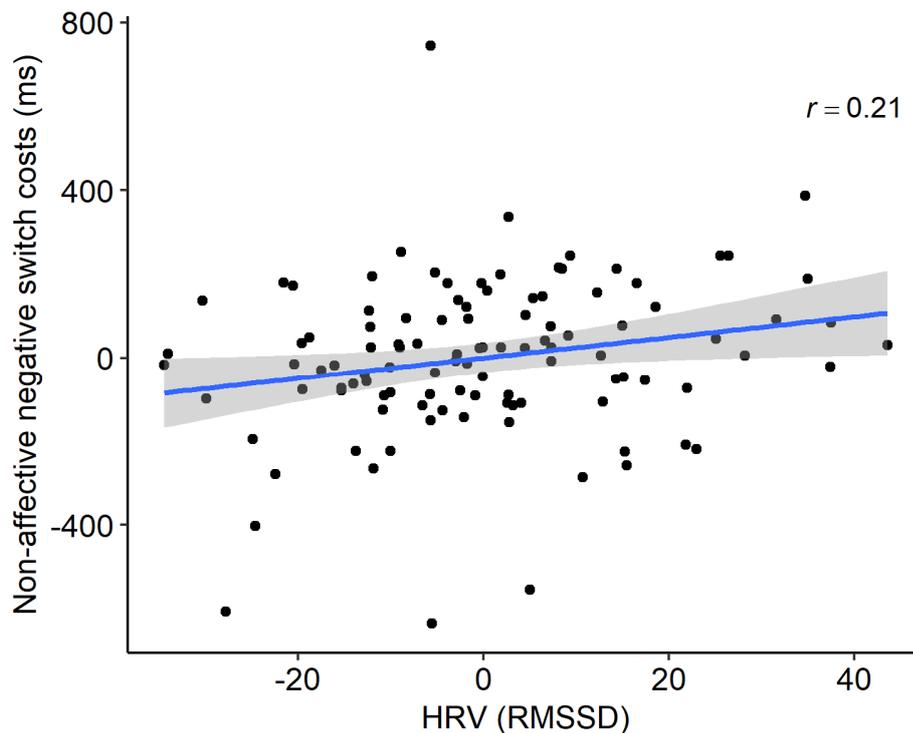


Figure 2: Partial correlation between non-affective negative switch costs and HRV (RMSSD).

Residuals from regressing non-affective negative switch costs on BPM, negative affective switch costs, positive non-affective switch costs and positive affective switch costs are plotted against the residuals from regressing RMSSD on BPM and the other switch costs. The Pearson correlation between these residual variables and the 95% CI interval are displayed.

Discussion

The neurovisceral integration model summarizes the relationship between the central nervous system and the autonomous nervous system (Thayer et al., 2009; Thayer & Lane, 2000). Vagally mediated heart rate variability provides an index of the influence of the parasympathetic nervous system, that is, a measure of cardiac vagal tone. The neurovisceral integration model aims to account for the complex interplay between autonomic, cognitive and emotion regulation systems through their support by a common cortico-subcortical neural network. According to the

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

model, higher resting HRV reflects better functioning of this neural network, supporting better self-regulation and adaptation to changing situational demands. The relationship between autonomic regulation and cognitive control has previously been shown, with higher levels of resting HRV being associated with better monitoring and updating of working memory, attention control, response inhibition, and greater cognitive flexibility (Colzato et al., 2018; Hovland et al., 2012; Thayer et al., 2009; Zahn et al., 2016). Although greater cognitive flexibility is generally considered beneficial for adaptability to the environment, adding affective information can create ‘contexts’ where different cognitive responses could be required to meet the demands of a situation. The aim of the current study was therefore to investigate the association between vagally mediated resting HRV and cognitive flexibility in the context of affective information, to increase our understanding of the relationship between autonomic, cognitive and affective systems.

More efficient shifting (i.e. greater flexibility) from non-affective aspects towards affective aspects of positive information has previously been associated with more effective reappraisal use and smaller increases in anxiety over time (Malooly et al., 2013; Twivy et al., 2019 unpublished manuscript). Because individual differences in anxiety (Friedman, 2007) and emotion regulation (Appelhans & Luecken, 2006; Thayer & Brosschot, 2005) have been linked to resting HRV, we expected more efficient shifting towards affective aspects of positive information also to be associated with higher resting HRV. However, we did not find support for such a relationship. Whereas the majority of work on HRV and attention regulation for emotional information has focused on negative/threatening stimuli, it is possible that the link between resting HRV and attention regulation for positive information is relatively weaker.

We did find support for an association between more efficient shifting of attention from affective to non-affective aspects of negative information and lower resting HRV. At first sight

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

this may seem to contradict the neurovisceral integration model that predicts higher resting HRV to be associated with more flexibility (Thayer et al., 2009; Thayer & Lane, 2000). Although facilitated attention to negative information, lower resting HRV and anxiety are indeed interlinked (Cisler & Koster, 2010; Friedman, 2007; Park & Thayer, 2014), research shows that anxious individuals actually show attentional avoidance when presented with negative information for longer durations. Such attentional avoidance may reflect a more strategic process underlying emotion regulation goals (Cisler & Koster, 2010). In line with the avoidance model of anxiety and worry (Borkovec et al., 2004) and empirical evidence of attentional avoidance in anxiety, we recently found that more efficient shifting of attention from affective to non-affective aspects of negative information predicted greater increases in anxiety across time (Twivy et al., 2019 unpublished manuscript). As stimulus presentation in the task switching paradigm is relatively long and we look at set shifting across trials, we're more likely tapping into such strategic processes. Our findings thus fit with the neurovisceral integration model, such that more efficient shifting of attention towards non-affective aspects of negative information, which can facilitate attentional avoidance of negative information linked to anxiety (Cisler & Koster, 2010), is related to lower resting HRV.

These findings also add to a growing notion that flexibility can be less adaptive in certain circumstances and that it is important to consider the (emotional) context (Parsons, Kruijt, & Fox, 2016). When increased flexibility could facilitate attentional avoidance of negative information, it may obstruct learning that negative information does not always result in an aversive outcome, preventing threat associations to be altered by extinction learning or habituation (Borkovec et al., 2004). A relative inflexibility when shifting attention away from affective aspects of negative information could thus contribute to better functioning in the long-term. Similarly, inflexibility when shifting attention away from affective aspects of negative information may also facilitate

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

some form of 'situation awareness', that is, comprehending the meaning of a situation. To make adequate decisions in (negative) situations it is necessary to have situation awareness. Situation awareness has mostly been studied in contexts where human errors can occur (e.g. police command, health care). A previous study on situation awareness training in a policing context showed positive correlations between resting HRV and situation awareness scores (Saus et al., 2006). In an analogous way, adaptation to demands of a dynamic environment may rely on the regulation of attention in ways that allow for assessment of an affectively-loaded situation to comprehend the meaning of the situation.

The association between less flexible shifting of attention from affective to non-affective aspects of negative information and higher resting HRV is thus in agreement with the neurovisceral integration model such that it could facilitate self-regulation and adaptive functioning in a dynamic environment over time. Whereas previous work relates greater cognitive flexibility to higher resting HRV when measured as a single construct in the context of non-affective information, we reveal the need for a more nuanced view when assessing attention regulation in the context of affective information, specifically concerning shifting to non-affective aspects of negative information. Finally, it is important to note that the association between flexibility in shifting attention towards non-affective aspects of negative information and HRV was small, but this is in line with meta-analytical evidence for the relationship between HRV and executive function (Zahn et al., 2016).

A few limitations to the study should be discussed. First, our sample consisted mostly of young, healthy adults so it remains unclear to what extent our findings generalize to other populations. Moreover, the nature of our population could also explain why no relationship was observed between trait anxiety, depressive symptoms and HRV. Although previous research has found this relationship (Friedman, 2007; Kemp et al., 2010), our population reported low levels

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

and relatively little variability in measures of trait anxiety (STAI-T) and depressive symptoms (BDI). Second, vagally mediated HRV seems to be sensitive to a range of factors such as age, gender, smoking, weight, cardioactive medication, physical activity, heart rate and more (for an overview see Laborde et al., 2017). Although we examined the relationship between some factors and HRV in the current sample, and excluded individuals using psychoactive or cardioactive medication, we cannot rule out that other unmeasured factors have influenced our results. Similarly, there is continued debate around respiratory control (Laborde et al., 2017). We did not measure respiratory rate and let participants breathe spontaneously, but we used RMSSD as our measure of vagally mediated HRV as this measure is less affected by breathing than HF-HRV and the effects of respiration on parasympathetic indices of resting HRV have shown to be minimal (Laborde et al., 2017). Finally, it is important to note that correlation is not causation, so based on our findings we cannot draw any conclusions about the direction of the relationship between resting HRV and affective flexibility. As has been suggested before (Colzato et al., 2018), it would be interesting for future research to manipulate vagal control through transcutaneous vagal nerve stimulation and examine the effects on affective flexibility.

In summary, the current findings support the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000) such that individual differences in resting HRV relate to performance on a cognitive control task, possibly because of common underlying cortico-subcortical neural circuits supporting these processes. We extend previous work by investigating the association between resting HRV and cognitive flexibility (i.e. set shifting) in the context of affective information, demonstrating the need for a nuanced view on the complex interplay between vagally mediated HRV, cognitive control and emotion.

HEART RATE VARIABILITY AND AFFECTIVE FLEXIBILITY

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Open Practices Statement

The data and analysis scripts for this study are available on the Open Science Framework: <https://osf.io/uqmfd/> This study was not preregistered.

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Supplemental Material

Additional Analyses on HRV and Affective Flexibility

We performed an additional hierarchical linear regression analysis with resting RMSSD as dependent variable and switch costs as predictors. Switch costs were now calculated as the percentage change from the non-switch baseline (rather than the raw RT difference). In a first step we entered resting heart rate (BPM) to the model to control for the average heart rate per minute. In the second step we entered the four types of switch costs.

The model with just BPM was significant, $F(1, 106) = 53.34$, $p < .001$, adj. $R^2 = 0.33$. Adding the four switch costs to the model did not significantly improve fit, $F(4,101) = 2.04$, $p = .094$, $\Delta R^2 = 0.05$.¹ BPM was negatively related to RMSSD with higher BPM related to lower HRV, $\beta = -0.59$, $t = -7.3$, $p < .001$. Non-affective negative switch costs were positively related to RMSSD, $\beta = 0.18$, $t = 2.18$, $p = .032$. Lower non-affective negative switch costs, that is, more efficient switching towards non-affective aspects of negative information was thus related to lower RMSSD. Neither affective negative ($\beta < -0.0041$), non-affective positive ($\beta = 0.11$), nor affective positive switch costs ($\beta = 0.06$) were significant predictors of RMSSD, all $ps > .10$.

¹Results are reported after exclusion of outliers based on standardized residuals. With this case, adding switch costs to the model marginally significantly improved fit, $F(4,103) = 2.09$, $p = .088$, $\Delta R^2 = 0.05$. The effect of non-affective negative switch costs was similar, $\beta = 0.19$, $t = 2.35$, $p = .021$. When only adding non-affective negative switch costs to the model with BMP, there is a significant improvement of fit, $F(1,104) = 5.93$, $p = .017$, $\Delta R^2 = 0.04$. The effect of non-affective negative switch costs was similar, $\beta = 0.19$.