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Heart rate variability and cognitive processing: The autonomic response to task demands

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ABSTRACT

This study investigated variations in heart rate variability (HRV) as a function of cognitive demands. Participants completed an execution condition including the psychomotor vigilance task, a working memory task and a duration discrimination task. The control condition consisted of oddball versions (participants had to detect the rare event) of the tasks from the execution condition, designed to control for the effect of the task parameters (stimulus duration and stimulus rate) on HRV. The NASA-TLX questionnaire was used as a subjective measure of cognitive workload across tasks and conditions. Three major findings emerged from this study. First, HRV varied as a function of task demands (with the lowest values in the working memory task). Second, and crucially, we found similar HRV values when comparing each of the tasks with its oddball control equivalent, and a significant decrement in HRV as a function of time-on-task. Finally, the NASA-TLX results showed larger cognitive workload in the execution condition than in the oddball control condition, and scores variations as a function of task. Taken together, our results suggest that HRV is highly sensitive to overall demands of sustained attention over and above the influence of other cognitive processes suggested by previous literature. In addition, our study highlights a potential dissociation between objective and subjective measures of mental workload, with important implications in applied settings.

1. Introduction

A large body of research has shown a direct link between cognitive processing and the cardiovascular system through autonomic vagal control (Thayer & Lane, 2009). A simple way of measuring that relationship is to look at heart rate variability (HRV), a non-invasive measurement of the interactions between the autonomic nervous system and the cardiovascular system, based on the study of oscillations of the interval between heartbeats (Malik et al., 1996; Pumprla, Howorka, Groves, Chester, & Nolan, 2002).

Thayer et al. have recently proposed the Neurovisceral Integration Model to account for the link between cognitive processing and the functioning of the autonomous nervous system (Thayer, Hansen, Saus-Rose, & Johnsen, 2009; Thayer & Lane, 2009). They pointed out that HRV is a particularly sensitive index of the changes in a flexible neural network that is dynamically organized in response to situational requirements. The authors highlighted the role of the prefrontal cortex in the modulation of subcortical cardio-acceleratory circuits via an inhibitory pathway that is associated with vagal function and that can be indexed by HRV. The link of the frontal cortex to autonomic motor circuits responsible for both the sympathoexcitatory and parasympathoinhibitory effects on the heart seems to be controlled both by direct and indirect pathways. In this sense, one of the potential mediators underlying variations in HRV as a function of cognitive demands is the baroreceptor system, i.e., the negative feedback loop adjusting heart activity to blood pressure fluctuations. In fact, the baroreflex function appears to be influenced by specific behavioral manipulations of cognitive demands and mental workload (e.g., Duschek, Werner, & Reyes del Paso, 2013; Paso, González, & Hernández, 2004). Consequently, variations in the baroreflex function may therefore also mediate modulations in HRV during the specific task conditions. In any case, HRV is thought of as an overall index of central-peripheral neural feedback and central nervous system–autonomic nervous system integration (Thayer & Lane, 2000, 2009).

A cursory look to the literature on the relationship between HRV cognition shows that researchers have used a wide range of tasks,

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tapping different cognitive processes, which make it difficult to establish a finer-grained relationship between HRV and cognitive processing. In more specific terms, a number of studies have singled out a subset of mental workload components – executive demands – as key to understand the HRV-cognitive processing link, with lower HRV as executive demands increase (Backs & Seljos, 1994; Duschek, Muckenthaler, Werner, & Reyes del Paso, 2009; Hansen, Johnsen, & Thayer, 2003; Luft, Takase, & Darby, 2009; Mathewson et al., 2010; Mulder & Mulder, 1981). In this scenario, the above mentioned Neurovisceral Integration Model predicts an inverse relationship between executive task demands and levels of HRV, which seems to be confirmed by the studies cited above. However, the results of other studies appear to challenge this straightforward view of the relationship between HRV and cognitive processing. For instance, Fairclough and Houston (2004) failed to show differences between the congruent and incongruent conditions when participants had to name the color of the ink in a Stroop task, a well-known executive task (e.g., Egner & Hirsch, 2005). On the contrary, they showed that HRV was sensitive to time-on-task, pointing to the role of overall attention demands on HRV. In this same line, Chang and Huang (2012) showed that HRV varied as a function of attentional demands in a visual search task, with lower HRV in a conjunction search task than in a feature search task and a control condition in which participants passively watched to the stimuli.

Together with attention demands, perceptual difficulty seems to be another key factor modulating HRV. The results of two recent studies point in that direction. Chen, Tsai, Biltz, Stoffregen, and Wade (2015) reported lower HRV as a function of perceptual difficulty, but not as a function of working memory load (linked to executive functioning, e.g., Duncan & Owen, 2000). Particularly relevant here is the study by Luque-Casado, Zabala, Morales, Mateo-March, and Sanabria (2013), who compared HRV during performance of three tasks, tapping three different cognitive functions: the psychomotor vigilance task (PVT; a vigilance task), an endogenous temporal orienting task (a cognitive control task), and a duration discrimination task (a perceptual task). The results showed lower levels of HRV in the perceptual task than in the other two tasks, with no significant differences in the main indexes of HRV between the PVT and the temporal orienting task. In addition, they showed that HRV decreased with time-on-task, a result that did not seem to depend on the particular task running at that moment.

Overall, the outcome of the above-mentioned studies seem to nuance Thayer et al.'s Neurovisceral Integration Model, and point to some aspects of cognitive demand (i.e., perceptual difficulty and sustained attention) and not others (working memory i.e., workload, interference) as key task features modulating HRV. However, as Luque-Casado et al. acknowledged in their article, brain structures typically associated with executive processing seem to be also involved in difficult perceptual discrimination (Duncan & Owen, 2000). Thus, the question remains of whether a task purposely developed to involve high executive demands would induce a larger reduction in HRV than the perceptual task used by Luque-Casado et al. (2013).

The present study is aimed at further investigating the role of particular processing demands involved in task effects on HRV. We partially replicated Luque-Casado et al.'s (2013) manipulation, using the PVT and the duration discrimination task, but replaced the temporal orienting task by a N-back task. The N-back task tackles working memory capacity, a core component of executive functioning, by asking participant to tag and update short-term stored information on a trial-by-trial basis (Kirchner, 1958; Owen, McMillan, Laird, & Bullmore, 2005). Importantly, along with these three tasks, we included three parallel oddball tasks, with the same stimuli parameters for each of the three, but in which participants just had to detect a rare event within a sequence of frequent stimuli.

The inclusion of the oddball condition allowed us to control for an important aspect that has been neglected in the majority of previous studies investigating the relationship between HRV and cognitive processing: the potential influence of stimulus parameters of the task on the relationship between autonomic response and cognitive performance. That is, whether stimulus setting features (e.g., stimulus duration, inter-stimulus interval) may explain (at least partially) the influence of task performance on autonomic reactivity over and above any specific cognitive process (e.g., executive processing, memory, etc.) specifically tapped by the task. In this sense, to the best of our knowledge, the only task feature that has been investigated in relation to this issue is the motor activity during the cognitive task (Bush, Alkon, Obradović, Stamperdahl, & Boyce, 2011; Porges et al., 2007). While Porges et al. showed that only gross motor activity (e.g., bike pedaling) could modulate the relationship between autonomic response and cognitive processing, Bush et al. found changes on autonomic reactivity to various cognitive tasks that were related to the particular motor activity during each procedure. Here, by asking participants to perform an oddball version of the three main cognitive tasks we controlled for variations in HRV due to the particular stimulus features of the tasks (e.g., stimulus duration) regardless of the task demands, whilst largely reducing the motor activity.

Here, as a cross-task and cross-condition manipulation check, subjective mental load was assessed with the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire (Hart & Staveland, 1988). The NASA-TLX sensitivity to mental workload has been demonstrated to be useful in a variety of cognitively demanding tasks such as aircraft piloting (Karavidas et al., 2010; Ma et al., 2014), air traffic control (Brookings, Wilson, & Swain, 1996), surgery (Zheng et al., 2012), or laboratory tasks context (Muth, Moss, Rosopa, Salley, & Walker, 2012). With the inclusion of the NASA-TLX we aimed at comparing objective (HRV) and subjective potential indices of mental load induced by the different task demands. This is not trivial since previous research has questioned the validity of subjective measures of mental load (see Annett, 2002 for discussion on this issue).

On the basis of Luque-Casado et al.'s (2013) findings and the previous related research, we expected the N-back task to exert a stronger modulation over HRV than the PVT. The question of interest was to see whether the N-back task would also influence HRV to a greater extent than the duration discrimination task, a result that would add further support to the Neurovisceral Integration Model. Importantly, given that the three tasks in the oddball condition were essentially the same task (with variations only in stimuli parameters) with minimal response requirements, we did not expect significant differences in HRV across them. We predicted the NASA scores to parallel the HRV results, with larger perceived workload in the N-back task than in the other two tasks, and no differences across the three oddball tasks.

2. Methods and design

2.1. Participants

Twenty-four males undergraduate students (age range: 18–28 years old; $M = 21$ years old; SD = 2.6 years old) from the University of Granada (Spain) took part in the study in exchange of course credits. In order to take part in the experiment, participants were required to maintain a regular sleep–wake cycle for at least one day before the study and to abstain from stimulating beverages or any intense physical activity for the day of the experiment. Once in the laboratory, none of them reported having had any stimulating beverage or exercise session, and they all reported a regular sleep the night before (6–10 h; $M = 7.5$; SD = 0.9). None of the participants