



Factors influencing the role of cardiac autonomic regulation in the service of cognitive control

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ABSTRACT

Working from a model of neurovisceral integration, we examined whether adding response contingencies and motivational involvement would increase the need for cardiac autonomic regulation in maintaining effective cognitive control. Respiratory sinus arrhythmia (RSA) was recorded during variants of the Stroop color-word task. The Basic task involved “accepting” congruent items and “rejecting” words printed in incongruent colors (BLUE in red font); an added contingency involved rejecting a particular congruent word (e.g., RED in red font), or a congruent word repeated on an immediately subsequent trial. Motivation was increased by adding a financial incentive phase. Results indicate that pre-task RSA predicted accuracy best when response contingencies required the maintenance of a specific item in memory or on the Basic Stroop task when errors resulted in financial loss. Overall, RSA appeared to be most relevant to performance when the task encouraged a more proactive style of cognitive control, a control strategy thought to be more metabolically costly, and hence, more reliant on flexible cardiac autonomic regulation.

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1. Introduction

Models of neurovisceral integration (Benarroch, 1993, 1997; Critchley, 2005; Porges, 1995; Thayer & Lane, 2000, 2009) posit the simultaneous engagement of autonomic, attentional, and emotional systems in the support of self-regulation and adaptive behavior. Respiratory sinus arrhythmia (RSA) is the high frequency variation in the beat-to-beat interval of heart rate that accompanies normal respiration. It is considered an index of parasympathetic cardiac control and a marker of autonomic flexibility in adapting to environmental demands (Beauchaine, 2001; Berntson et al., 1997; Porges, 1995; Thayer & Lane, 2000, 2009). RSA is modulated by a set of midbrain and higher cortical regions that include the insular cortex, anterior cingulate cortex (ACC), the ventromedial prefrontal cortex (PFC), the central nucleus of the amygdala, and the hypothalamic nuclei (Benarroch, 1993, 1997; Critchley, 2005; Critchley, Corfield, Chandler, Mathias, & Dolan, 2000; Matthews, Paulus, Simmons, Nelesen, & Dimsdale, 2004; Ter Horst & Postema, 1997). Together, these structures are considered part of a central

autonomic network (CAN), and several of these structures also play a critical role in the implementation of cognitive control over attentional resources (e.g., Benarroch, 1993, 1997; Critchley, 2005). It is this observation that has fueled a growing interest in specifying the role that RSA plays in supporting cognitive performance, especially when the need for cognitive control is high.

There is some confirmation, particularly in child research, that individual differences in RSA are associated with various indices of performance in situations where cognitive control is required (Chapman, Woltering, Lamm, & Lewis, 2010; Marcovitch et al., 2010; Staton, El-sheikh, & Buckhalt, 2008). Research with adults is still in its early stages, but some studies have provided evidence of associations between RSA and cognitive performance. For example, higher baseline (resting) RSA in younger adults has been shown to relate to enhanced performance on sustained attention tasks that require the identification of various target stimuli (Hansen, Johnsen, & Thayer, 2009) and on *n*-back tasks that require the use of working memory (Hansen, Johnsen, Sollers III, Stenvik, & Thayer, 2004; Hansen, Johnsen, & Thayer, 2003; Hansen et al., 2009). Higher baseline RSA in both older and younger adults has also been shown to relate to enhanced performance on a spatial touch-screen maze task in which performance on one trial is relevant to performance on the next trial for that maze (Mathewson, Dywan, Snyder, Tays, & Segalowitz, 2011). In addition, recent work with middle-aged men

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demonstrated that those with higher resting RSA performed better on a verbal selective reminding task (Shah et al., 2011). Thus, there is some support for the view that higher baseline RSA is associated with enhanced performance on a range of cognitive tasks, not just in children, but in other age groups as well. So, it would seem that individuals with higher baseline RSA may be more able to modulate arousal so as to facilitate performance during cognitively demanding situations.

We note, however, that baseline measures of RSA have not always proved relevant to cognitive performance. In fact, rather than higher baseline RSA, the best predictors can be lower levels of on-task RSA or greater RSA reactivity (i.e., greater reductions in RSA from baseline to task). Children and adolescents with lower on-task RSA performed more accurately on an affectively arousing Go/NoGo task (Chapman et al., 2010). Similarly, younger adults with lower on-task RSA and greater RSA reactivity made fewer mistakes on a rapid visual search task that required the use of both selective and sustained attention (Duschek, Muckenthaler, Werner, & Reyes del Paso, 2009). In addition, younger and middle-aged adults with greater RSA reactivity were also found to execute correct responses more quickly in the context of an emotional Stroop task (Mathewson et al., 2010). This pattern of results suggests that lower on-task RSA and larger decreases in RSA from baseline to task are associated with enhanced cognitive performance. This on-task reduction in RSA may be beneficial to performance because it represents a reduction in parasympathetic influence so as to allow for the mobilization of resources necessary to meet the demands of the cognitive challenge at hand.

There is some evidence that relations between RSA and performance are most likely to emerge when tasks require higher level executive functions. For instance, Hansen et al. (2003) reported a relationship between higher baseline RSA and better performance on tasks that required sustained attention and working memory, an association that did not emerge in the context of a simpler response time task. However, we note that even when executive functions are involved, relationships between RSA and performance are not always seen. For instance, we found no apparent influence of pre-task RSA in a sample of older and younger adults who were asked to complete a working memory inhibitory control (WMIC) task (Capuana, Dywan, Tays, & Segalowitz, 2012). The WMIC task, initially developed by Hester and Garavan (2005), is a Go/NoGo task that requires participants to withhold responding to items they are currently maintaining in working memory. We manipulated task difficulty by utilizing increasingly larger working memory (WM) loads. We did find that higher pre-test levels of cardiac workload, as measured by Rate Pressure Product (RPP), were related to inhibitory control errors in older adults, which is consistent with there being some general role for cardiac autonomic regulation in supporting task performance; however, relations with RSA did not emerge (Capuana et al., 2012). This was the case for both older and younger adults at all three levels of task difficulty. Similarly, Britton et al. (2008) found that resting RSA was not related to the performance of middle-aged adults on a cognitive battery that included tests of verbal meaning and inductive reasoning. Of course, since RSA is known to decline with age (e.g., De Meersman & Stein, 2007), it may be more difficult to demonstrate such relations in middle to older-aged adults. Even so, inconsistencies in relations between various baseline measures of RSA (pre-task, resting) and performance suggest that the specific nature of the cognitive challenge may be relevant to this association (see also, Morgan, Aikins, Steffian, Coric, & Southwick, 2007; Pu, Schmeichel, & Demaree, 2010) and, as such, a more strategic approach to task design might help clarify the conditions in which associations between RSA and cognitive function are likely to emerge.

1.1. Increasing response contingencies

Whether cardiac autonomic regulation contributes in a meaningful way to (or is a result of) better executive control, one might expect this relationship to become increasingly evident as the difficulty of an executive control task increases. We note, however, that tasks often involve only one level of difficulty, so this hypothesis is rarely tested. Furthermore, in those cases when difficulty level has been manipulated, the relationship between autonomic regulatory control and performance remained constant. For instance, Mathewson et al. (2011) examined the relationship between RSA and spatial memory performance as participants navigated their way through a maze that was hidden in a square grid. In order to determine whether the association between RSA and performance increased in response to enhanced spatial memory requirements, they increased grid sizes from 4×4 to 6×6 to 8×8 . Mathewson et al. confirmed that higher baseline RSA was associated with better performance on all three levels of the task; however, the size of the relationship between task performance and RSA did not change in response to the augmented spatial memory load.

Importantly, there are other ways to enhance task difficulty. One route involves manipulating the number of rules or contingencies that guide appropriate response selection within a task (Bunge, 2004; Bunge, Kahn, Wallis, Miller, & Wagner, 2003; Bunge & Zelazo, 2006). Effective rule-use is a hallmark of adaptive cognitive control in that it facilitates the selection of actions compatible with current goals (Bunge & Zelazo, 2006). Several neuroimaging studies have demonstrated that, as the representations required for response selection become increasingly abstract, activation within the PFC increases systematically in more anterior regions (Badre & D'Esposito, 2007, 2009; Badre, Kayser, & D'Esposito, 2010; Koehlin & Jubault, 2006; Koehlin, Ody, & Kouneiher, 2003). In one particularly elegant study, Badre and D'Esposito (2007) examined frontal activation while participants completed four different types of response-control tasks. Difficulty was manipulated *between* the four tasks by gradually increasing the number of rules required for response selection. Difficulty was also manipulated *within* each task by systematically increasing response competition or load. Results confirmed that, as the number of response contingency rules increased across the four tasks, activation primarily within premotor cortex expanded to include regions of the frontal polar cortex. Importantly, as response competition (i.e., load) increased within each task, the level of activation within a given region increased but remained fixed in terms of its location.

We found this dissociation between “within-task load” versus “between-task complexity” intriguing in that it might help explain some of the puzzling results in the RSA-cognition studies. Recall that Mathewson et al. (2011) reported a relationship between RSA and performance during a spatial maze task, but note that this relationship did not increase in response to larger spatial memory loads. Thus, rather than increasing the size of the memory load within a task, perhaps a more meaningful way to examine relations between RSA and performance would be to manipulate the number of contingency rules that need to be maintained in order to execute an appropriate response in a given task context.

1.2. The role of arousal

In addition to manipulating response contingency rules, we were interested in examining whether the relationship between RSA and cognitive performance would increase in strength when we increased the level of arousal elicited by the task. The ability to maintain cognitive control under arousing circumstances would require appropriate emotion regulation which, in turn, would be expected to involve an even greater dependence on cardiac autonomic regulation (Beauchaine, Gatzke-Kopp, & Mead,

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