International Journal of Psychophysiology 119 (2017) 87–92

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

How effortful is cognitive control? Insights from a novel method measuring single-trial evoked beta-adrenergic cardiac reactivity

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ARTICLE INFO

Article history:
Received 14 July 2016
Received in revised form 6 October 2016
Accepted 8 October 2016
Available online 11 October 2016

Keywords:
Cognitive control
Effort
Pre-ejection period
Heart rate
Orienting response

ABSTRACT

The ability to adjust attentional focus to varying levels of task demands depends on the adaptive recruitment of cognitive control processes. The present study investigated for the first time whether the mobilization of cognitive control during response-conflict trials in a flanker task is associated with effort-related sympathetic activity as measured by changes in the RZ-interval at a single-trial level, thus providing an alternative to the pre-ejection period (PEP) which can only be reliably measured in ensemble-averaged data. We predicted that response conflict leads to a physiological orienting response (i.e. heart rate slowing) and increases in effort as reflected by changes in myocardial beta-adrenergic activity (i.e. decreased RZ interval). Our results indeed showed that response conflict led to cardiac deceleration and decreased RZ interval. However, the temporal overlap of the observed heart rate and RZ interval changes suggests that the effect on the latter reflects a change in cardiac preload (Frank-Starling mechanism). Our study was thus unable to provide evidence for the expected link between cognitive control and cardiovascular effort. However, it demonstrated that our single-trial analysis enables the assessment of transient changes in cardiac sympathetic activity, thus providing a promising tool for future studies that aim to investigate effort at a single-trial level.

1. Introduction

In daily life, there are many situations in which we have to maintain focus without being distracted, so that inappropriate responses do not occur. The ability to flexibly adapt behavior to current task demands is generally considered to be an important aspect of cognitive control (Kahneman, 1973). Cognitive control processes are typically measured in response inhibition tasks, such as the flanker task (Eriksen and Eriksen, 1974; for an overview see Eriksen, 1995), in which the amount of conflict can be manipulated. According to the conflict-monitoring theory (Botvinick et al., 2001) cognitive control is adaptively mobilized when response conflict is detected during a trial. This adaptation to conflict improves subsequent performance and is thought to reflect transient enhancements in cognitive control. In addition, when the proportion of conflict trials across a task block is high, these adaptations result in an overall reduction in the behavioral susceptibility to conflict, suggesting improved sustained cognitive control during a high-conflict task block (Botvinick et al., 2001; Gratton et al., 1992; Purmann et al., 2011).

In the present study we investigated whether the transient and sustained mobilization of cognitive control is also associated with physiological responses typically interpreted as reflecting effort mobilization. Although cognitive control has often been characterized as a process requiring effort (Hasher and Zacks, 1979; Kahneman, 1973; Mulder, 1986; Schneider and Shiffrin, 1977; Westbrook and Braver, 2015; see also Rothbart et al., 2003) there is little empirical evidence to support this notion. Only a few studies have established a link between cognitive control and effort based on demonstrating an increase in pupil dilation in response to conflict trials in cognitive control paradigms (Brown et al., 1999; Laeng et al., 2011; Rondeel et al., 2015; Siegle et al., 2008; Siegle et al., 2004; van Bochove et al., 2013; van Steenbergen and Band, 2013; van Steenbergen et al., 2015; Wendt et al., 2014). However, although increased pupil dilation has been argued to reflect increased effort (Kahneman, 1973), it might simply reflect an increase in physiological arousal non-specific to effort mobilization (Bradley et al., 2008). The same issue might apply to studies that have interpreted increased effort based on observed skin conductance

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http://dx.doi.org/10.1016/j.ijpsycho.2016.10.007

changes in response to conflict trials (Kobayashi et al., 2007; Naccache et al., 2005; Stennett, 1957; cf. Schacht et al., 2010).

The present study used cardiac physiological measures as an alternative to pupil dilation and skin conductance. In particular, we focused on myocardial sympathetic activity as the operational definition of effort mobilization (Wright, 1996). Previous use of cardiovascular measures to index effort has typically analyzed cardiovascular responses at the block of trials level, thus aggregating the cardiovascular response over several minutes of task performance. For example, Richter and colleagues (Richter et al., 2008) demonstrated increases in mean heart rate of a 72 trials block in proportion to experienced task difficulty. However, given that the cardiovascular system is controlled by both branches of the autonomic nervous system (Berntson et al., 2007), heart rate can only be regarded as a measure of effort if the sympathetic activation (i.e. increase in heart rate) outweighs the parasympathetic activity (i.e. decrease in heart rate), and it is impossible to disentangle these influences using a noninvasive methodology.

A more promising measure of effort mobilization is the pre-ejection period (PEP) (Gendolla et al., 2012; Kelsey, 2012; Richter et al., 2008). PEP is defined as the period between the onset of left ventricular contraction and aortic valve opening (Weissler, 1977) and has been considered to be a useful indicator of the contractile state of the heart (Kelsey, 2012; Sherwood et al., 1990). Consistent with our definition of effort mobilization (Kelsey, 2012), PEP is thought to reflect the sympathetic effects on the heart, mediated by its beta-adrenergic receptors, and has been shown to respond proportionally to task engagement (Richter et al., 2008). Further, research has shown that PEP becomes progressively shorter in response to increasing task difficulty (Richter et al., 2008; Silvestrini and Gendolla, 2013). It is important to note that these effects of decreased PEP were observed in the absence of a decrease in heart rate. This is important because heart rate slowing is associated with greater ventricular filling (cardiac pre-load) which automatically leads to increased contractility and decreased PEP via the Frank-Starling mechanism. Thus, heart rate deceleration influences PEP independently of sympathetic influences (Sherwood et al., 1990).

Some studies have also investigated the effect on cardiac reactivity at the level of single trials. To the best of our knowledge, however, this approach has yet only been used for heart rate measures. For example, heart rate slowing has been observed following attention regulation (Somsen et al., 2000), error monitoring (Hajcak et al., 2003), mental transformations (Jennings et al., 2003), and response conflict (Fiehler et al., 2004; Jennings et al., 1991; Schacht et al., 2010; cf. Spapé and Ravaja, 2016). This transient deceleration of heart rate after stimulus onset has been interpreted to reflect an orienting response, mediated by the parasympathetic system, that helps to prepare organisms to deal effectively with task-relevant stimuli (Graham and Clifton, 1966; Jennings et al., 1991; Lynn, 1966; van der Molen, 2000).

The goal of the present study is to examine whether conditions that require increased cognitive control lead to effort mobilization as measured at a single-trial level. To this aim we developed a – to the best of our knowledge – novel method that provides an alternative measure of beta-adrenergic sympathetic impact on the heart at a single-trial level. The standard approach to measure PEP requires ensemble-averaged ICG data across many R-peaks in which PEP is typically defined as the time interval between the Q point and the B point. Given the complexity of this scoring method, guidelines have been developed to standardize visual inspection and correction (Sherwood et al., 1990). However, this method is not suitable to be applied at the single-trial level because the Q and B points are both considerably susceptible to noise and distortion. Fortunately, it has been shown that for signals ensemble-averaged over 1 min epochs, PEP can be closely approximated by measuring the interval between the R-peak and the Z (dZ/dt_{max}) points (Lozano et al., 2007), which are fairly simple to extract, even for single QRS cycles. Given this close relationship between PEP and the RZ interval (henceforth abbreviated as RZ), the method introduced here capitalizes on this finding and will measure effort-related beta-adrenergic sympathetic impact on the heart by calculating an evoked response at trial level based on an interpolated continuous RZ signal.

Using this novel method, we tested the primary hypothesis that conflicting flanker task trials do not only decrease heart rate, but also increase transient effects on compensatory effort, as reflected by a lowering of evoked RZ following stimulus onset. Physiological data was acquired in the context of a conflict tasks in which participant had to respond to conflict and no-conflict flanker trials presented in random order. In addition, the proportion of conflict trials across a task block was manipulated, using low-conflict (75% no-conflict and 25% conflict trials) and high-conflict (25% no-conflict and 75% conflict trials) task blocks that were presented in alternating order. On the basis of the known temporal dynamics of beta-adrenergic influence on the heart (Mokrane and Nadeau, 1998; Ng et al., 2001), it is expected that the effects of trial conflict on RZ only emerge after 1 to 3 s following stimulus onset. On the other hand, based on earlier studies it is expected that the effect of trial conflict on cardiac deceleration emerges approximately 1 s after stimulus onset (i.e., the first interbeat interval following stimulus onset) and lasts for about 1 s (Fiehler et al., 2004; Jennings et al., 1991; Spapé and Ravaja, 2016). In addition, we investigated the effect of the overall proportion of conflict in the task blocks. Given previous findings showing increased behavioral interference in blocks in which the proportion of conflict trials is low (e.g. Gratton et al., 1992; Purmann et al., 2011), we expected that low-conflict compared to high-conflict blocks 1) leads to more pronounced transient enhancements of effort, reflected by a larger effect of conflict on RZ following stimulus onset; and, 2) might be associated with reduced sustained effort, reflected by an increased RZ during the pre-stimulus baseline period.

2. Method

2.1. Participants

Forty-eight students at Leiden University (age mean = 19.06 years, SD = 1.34 years; 7 males; 8 left-handed) participated as part of gaining course credit. All participants were native Dutch speakers and signed informed consent prior to their inclusion in the study. The research protocol for this study was approved by the Psychology Research Ethics Committee at Leiden University. Participants were required to meet the following inclusion criteria: 1) 18–30 years of age, 2) no previous meditation experience, 3) absence of any cardiovascular problems or psychiatric disorders, and 4) no use of medication known to influence cognition or cardiovascular responses (e.g. antipsychotics or antidepressants) at the moment of inclusion and during the whole study. Three participants were excluded after screening of the physiological data. For two participants, the ICG signal was too noisy to analyze. One other participant was excluded because their physiological data demonstrated frequent ventricular ectopic beats across the experimental session.

2.2. Flanker task

Participants performed a modified version of the Eriksen flanker task (Eriksen and Eriksen, 1974) that included no-conflict (congruent) and conflict (incongruent) trials. We presented an arrow target stimulus that pointed to the left or to the right. This arrow target was surrounded by two arrows at either side that pointed to the same (congruent), or the opposite (incongruent) direction as the target arrow. Participants had to respond as fast and accurately as possible to the direction of the central arrow by using the "q" or "p" key on a standard keyboard. The stimuli (sized about 2.45° width × 0.25° height) were presented in black color on a gray background on a 17" monitor at a distance of about 70 cm from the participants' eyes. The flanker task was conducted using E-prime software version 2.0.10.356 (Psychology Software Tools, Pittsburgh, PA) and took about 15 min to complete.