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Psychological and neural mechanisms associated with effort-related cardiovascular reactivity and cognitive control: An integrative approach

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ABSTRACT

Numerous studies have assessed cardiovascular (CV) reactivity as a measure of effort mobilization during cognitive tasks. However, psychological and neural processes underlying effort-related CV reactivity are still relatively unclear. Previous research reliably found that CV reactivity during cognitive tasks is mainly determined by one region of the brain, the dorsal anterior cingulate cortex (dACC), and that this region is systematically engaged during cognitively demanding tasks. The present integrative approach builds on the research on cognitive control and its brain correlates that shows that dACC function can be related to conflict monitoring and integration of information related to task difficulty and success importance—two key variables in determining effort mobilization. In contrast, evidence also indicates that executive cognitive functioning is processed in more lateral regions of the prefrontal cortex. The resulting model suggests that, when automatic cognitive processes are insufficient to sustain behavior, the dACC determines the amount of required and justified effort according to task difficulty and success importance, which leads to proportional adjustments in CV reactivity and executive cognitive functioning. These propositions are discussed in relation to previous findings on effort-related CV reactivity and cognitive performance, new predictions for future studies, and relevance for other self-regulatory processes.

In more than a hundred studies, cardiovascular (CV) parameters have been used to assess effort mobilization during cognitive tasks (see Gendolla and Wright, 2005; Gendolla et al., 2012; Wright and Kirby, 2001, for reviews). Within this framework, the construct of effort is usually defined as the amount of resources people mobilize to carry out behavior (Gendolla and Wright, 2009), and empirical evidence supports the idea that CV reactivity during cognitive tasks is proportional to effort mobilization. This paradigm was mainly initiated by Wright (1996), who integrated the psychophysiological approach of Obrist (1981) with predictions of motivational intensity theory (Brehm and Self, 1989). The clear predictions derived from the theory, together with the objectivity and reliability of CV measures, resulted in a successful experimental paradigm to investigate the influence of different variables on effort mobilization such as task difficulty, perceived ability, and incentives, as well as mood states, implicit affect, and fatigue (Richter et al., 2016).

However, despite the large number of studies, psychological and neural processes underlying effort-related CV reactivity are not clearly determined to date. Previous research reported evidence on the integration between brain and autonomic correlates of mental effort, suggesting promising perspectives (Critchley et al., 2003), but the underlying mechanisms are still not completely understood (Radulescu et al., 2015). For instance, it remains relatively unclear how task-related information such as task difficulty or success importance is processed and integrated to result in CV changes during cognitive tasks. Moreover, it is still an open question whether CV reactivity is the direct product of brain regions that assume executive cognitive processing or, rather, the peripheral activation that accompanies these processes but which is determined by other regions.

The present approach aims to offer some ideas on these issues by considering research on the concept of cognitive control. Cognitive control can be defined as the engagement of elementary cognitive processes when automatic or habitual responses are insufficient to sustain behavior (Shackman et al., 2011). Accordingly, and as proposed in dual-process models (Norman and Shallice, 1986; Posner and Snyder, 1975; Shiffrin and Schneider, 1977), cognitive control can be conceptually associated with effortful mental processes because it is predicted to require effort in contrast to automatic or habitual processes that are not expected to require effort.

Cognitive control represents a largely investigated domain with numerous theories on psychological and cerebral processes (Engle and Kane, 2003; Jacoby et al., 1999; Kahneman, 1973; Posner and Presti, 1987). The present integration focuses on one stream of research that offers promising links with the effort-related CV paradigm: the conflict-monitoring hypothesis (Botvinick et al., 2001, 2004) and its recent development, the model of the expected value of control (Shenhav et

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al., 2013, 2016). As presented below, this theoretical framework on cognitive control might be informative to advance our understanding of the psychological and neural processes reflected in CV reactivity during cognitive performance.

The starting point of the present integration is empirical evidence revealing that one brain region, the dorsal cingulate cortex (dACC), is directly associated with the production of autonomic responses to cognitive challenges and therefore effort-related CV reactivity (Critchley et al., 2003). The integration then uses propositions from the EVC model that state that specific brain areas assume specific functions in the processing and integration of task-related information during cognitive control. The integration consists of a theoretical framework of propositions about the initiation of cognitive control and the brain areas that process task-related information and execute controlled processes, as well as how these brain areas are related to CV reactivity.

These propositions are then compared with predictions and findings related to motivational intensity theory, which is also central in the present manuscript. Motivational intensity theory was used to provide predictions on the interaction between task difficulty and success importance in the production of CV response to cognitive challenges. As presented earlier, ample empirical evidence supported these predictions on the effect of an input—task difficulty and success importance—on an output—effort assessed as CV reactivity. But how the input more precisely leads to the output is still an open question. The aim of the present integration is to propose a coherent framework to describe and understand what the psychological and neural processes between these input and output are. Comparing predictions and findings related to motivational intensity theory with the present integration might therefore provide informative insights into the underlying mechanisms of effortful cognitive processes.

To offer an overview of the effort-related CV paradigm for readers who are not familiar with it, the first section of the manuscript includes a presentation of 1) motivational intensity theory, 2) CV measures used in this paradigm, 3) research based on this paradigm, and 4) research on the brain correlates of CV measures during cognitive performance. The second section then presents research on cognitive control and the conflict-monitoring theory, which proposes brain processes and psychological functions associated with cognitive control. In the third section, the present integration is described, together with its implications regarding previous findings and new predictions. Finally, this integrative approach is more broadly discussed in the light of self-regulation.

1. Overview of the effort-related CV paradigm

1.1. Motivational intensity theory

Predictions of studies based on Wright (1996) are mainly drawn from motivational intensity theory (Brehm and Self, 1989), which aims to predict how much effort people exert in a task. As a basic assumption, this theory relies on the resource conservation principle, which postulates that people avoid wasting their resources because these resources are important for survival. Accordingly, individuals should not invest more resources than is required or justified by a given task to avoid wasting resources. Therefore, the theory predicts that individuals mainly use two different kinds of information to determine the level of effort they will mobilize. First, individuals evaluate the difficulty of the task at hand. Overall, due to the resource conservation principle, people are expected to invest little effort when they perceive a task as easy and stronger effort when they perceive it as difficult—i.e. no more than what is required by the task. Second, individuals consider their perception of success importance, which is related to incentive, reward, or satisfaction of needs associated with the task or the outcome of the task. However, in contrast to other motivational theories of that time (Fowles et al., 1982; Heckhausen, 1991; Weiner, 1992), the theory proposes that effort is not always proportional to success importance. Success importance is expected to influence the maximal level of effort that is justified, which does not always transpose to effort exertion.

Availability of the information about task difficulty determines when and how success importance may influence effort exertion. When individuals have no information about task difficulty (i.e. unclear task difficulty) or when they can choose the difficulty level of the task (i.e. unfixed task difficulty), effort is predicted to be proportional to success importance. To avoid wasting resources, individuals are expected to rely on success importance to determine their effort when they have no information about the amount of effort required by the task or when they can choose the amount of effort they are going to invest in the task. However, when people have enough information about the task to establish a reliable perception of difficulty (i.e. known and fixed task difficulty), the theory predicts that effort is proportional to subjective difficulty as long as success is possible and required effort is justified by success importance. Accordingly, when required effort is below the maximal level of effort that is justified by success importance, a lower effort is expected for an easy task, whereas a stronger effort is expected for a difficult task. But when required effort exceeds the maximal level of effort that is justified by success importance, the theory predicts that people will disengage from the task. In addition, when a task is considered impossible, people are expected to disengage. Disengagement is therefore expected when required effort is not justified by success importance or when it is clear that success is impossible whatever effort is mobilized. These predictions in the context of tasks with known and fixed difficulty are presented in Fig. 1.

Originally, the theory was proposed to predict goal valence according to the level of energization—i.e. effort—engaged in goal pursuit that was expected to be determined by task difficulty and success importance (see Wright and Brehm, 1989). The more energy people engaged to attain an outcome, the more attractive it was expected to be. But the focus of interest later moved from goal valence to effort itself as the main dependent variable. The predictions on effort were then specifically tested by using CV reactivity.

1.2. Effort-related CV reactivity

To test the predictions of motivational intensity theory on effort mobilization, Wright (1996) relied on findings from the psychophysiological research of Obrist (1981), which involved CV concomitants of behavioral states. In early work, Obrist investigated heart rate (HR), the number of heart contractions per minute, as a signal for emotionally or motivationally relevant events by using classical aversive conditioning (i.e. exposing individuals to inescapable aversive stimuli) or shock avoidance paradigms in animals (Obrist, 1976). Building on this research, further studies revealed several important findings.

First, different results were observed when considering the possibility of individuals controlling the outcome of an aversive situation. In classical conditioning, individuals cannot escape the aversive stimuli

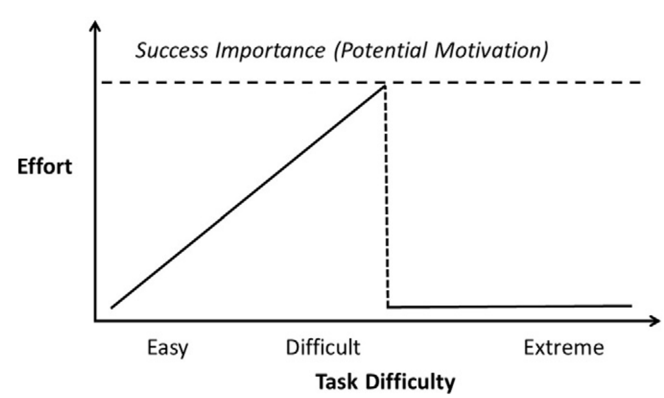

Fig. 1. Predictions of motivational intensity theory for known and fixed difficulty.