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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.

Keywords: effort; cardiovascular reactivity; cognitive control; conflict monitoring; anterior cingulate cortex; self-regulation

Psychological and Neural Mechanisms Associated with Effort-Related Cardiovascular Reactivity and Cognitive Control: An Integrative Approach

In more than a hundred studies, cardiovascular (CV) parameters have been used to assess effort mobilization during cognitive tasks (see Gendolla & Wright, 2005; Gendolla, Wright, & Richter, 2012; Wright & 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 (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., 2004, 2001) and its recent development, the model of the expected value of control (Shenhav et al., 2016, 2013). 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's integration (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 Figure 1.

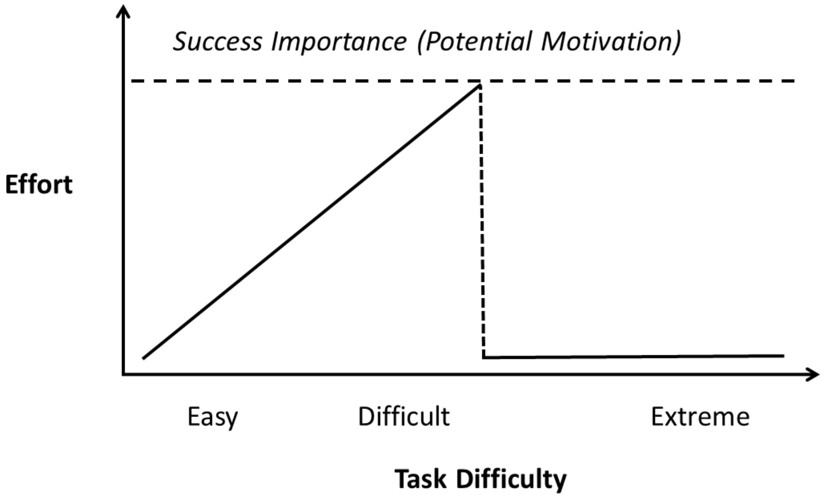

Figure 1. Predictions of motivational intensity theory for known and fixed difficulty.

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 & 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 (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 and therefore they have no control over the outcome of the situation. In contrast, individuals performing a shock avoidance paradigm can actively behave to avoid the aversive shock. Different types of CV responses were observed in both situations and this led to the distinction between situations in which individuals have no control of the outcome of a situation (i.e. a situation of *passive coping* in Obrist's terms) or have some control of the outcome (i.e. a situation of *active coping*), the latter corresponding to the situation of instrumental behavior in which the effort that people exert may contribute to goal attainment.

Regarding CV reactivity, findings revealed that situations of passive coping led to stronger vagal control of the heart (related to the parasympathetic branch of the autonomous system) and stronger vascular influence on blood pressure, whereas active coping led to stronger sympathetic control of the heart and stronger cardiac influence on blood pressure. This important finding indicated that CV reactivity in instrumental behavior is especially determined by sympathetic impact on the heart, which can be assessed through heart contractility—the force of heart contraction. Therefore, in integrating these findings, Wright (1996) focused on CV parameters strongly influenced by heart contractility as the most promising indicators of effort mobilization in instrumental behavior.

Among non-invasive CV parameters, systolic blood pressure (SBP), the maximal pressure between two heartbeats, is systematically influenced by sympathetic activity, given that SBP is determined by cardiac output and peripheral resistance and that cardiac output is influenced by heart contractility. In most studies initiated by Wright's integration (1996), SBP is therefore used as the most sensitive CV measure of effort. More recently, impedance cardiography was used in studies investigating effort-related CV reactivity to assess the pre-ejection period (PEP), the time interval between the beginning of the excitation of the left ventricle and the opening of the aortic valve, which offers a more direct measure of heart contractility and therefore effort (Richter et al., 2008; Silvestrini and Gendolla, 2011). PEP represents a more direct measure of sympathetic activity on the heart than SBP because SBP is also determined by total peripheral resistance (Levick, 2003), while PEP is almost exclusively influenced by heart contractility.

HR and diastolic blood pressure (DBP), the minimal pressure between two heartbeats, are also usually assessed together with PEP and SBP, but they are poorer indicators of effort because they are more strongly influenced by factors other than the sympathetic impact on the heart. HR is influenced by both sympathetic and parasympathetic impact and should only respond to effort when the sympathetic impact is stronger than the parasympathetic impact, which is not always the case (Obrist, 1981). DBP effects are more likely to be masked by changes in total peripheral resistance than are SBP responses (Levick, 2003). However, HR and DBP are useful to control for the preload or afterload effect that may influence PEP reactivity and should always be assessed together with PEP (Sherwood et al., 1990). Consequently, PEP in particular but also SBP were considered the main CV measures of interest in studies that investigated effort mobilization.

1.3. Empirical Evidence

Predictions of motivational intensity theory have been supported in numerous studies by using CV measures to assess effort mobilization. Beside the tests of the basic predictions of the theory regarding task difficulty and success importance, this paradigm was later used to investigate different factors that may influence task difficulty (e.g. perceived ability, mood, or implicit affect) or success importance (e.g. incentive, mood regulation, or ego involvement). Previous reviews summarized the findings of most of these experiments and these results are not presented here again (see Gendolla & Wright, 2005; Gendolla et al., 2012; Richter et al., 2016; Wright & Kirby, 2001, for reviews).

As a seminal example of a study assessing CV responses during cognitive performance, I will present here only the study of Richter and colleagues (Richter et al., 2008). The experiment started with a habituation period (8 min) during which resting values of CV activity (PEP, SBP, DBP, and HR) were assessed to determine baseline values. Then, following a between-subject design, participants performed a Sternberg short-term memory task (5 min) at one of four levels of task difficulty (easy, moderate, difficult, and impossible), during which CV reactivity was continuously assessed. For the analyses, a mean baseline value was calculated for each parameter and for each participant and subtracted from the activity during the task to obtain reactivity scores. That way, interindividual differences in terms of absolute CV values were removed from the main analyses. As predicted by motivational intensity theory, CV reactivity (mainly PEP and SBP) was expected to be low in the easy condition, stronger in the moderate condition, still stronger in the difficult conditions, and low again in the very difficult condition. Results completely supported the predictions for PEP and SBP.

As presented in this study and shown in numerous other studies, the CV paradigm provided strong support for the predictions of motivational intensity theory and its developments. However, the psychological and neural processes underlying CV reactivity during cognitive performance remain obscure. Researchers using this paradigm were mainly interested in the output of effort processes, but how this output is produced is still an open question. Regarding this issue, other research addressed the issue of brain correlates of mental effort and effort-related autonomic activity, suggesting promising perspectives (Critchley et al., 2003).

1.4. Previous Research on Brain Correlates of Effort-Related CV Reactivity

A number of studies addressed the issue of brain correlates of mental effort and its integration with autonomic activity during cognitive performance (see Critchley, 2005; Critchley et al., 2003; Gray & Critchley, 2012; Radulescu, Nagai, & Critchley, 2015). These studies consistently revealed a central role of one region of the brain in the sympathetic CV response to cognitive challenges: the dorsal anterior mid-cingulate cortex (dACC). Anatomically, the ACC is directly interconnected with autonomic nuclei in the hypothalamus and brain stem, as well as with several other regions that project within these homeostatic centers (Barbas et al., 2003; Critchley, 2004). Autonomic nuclei in the hypothalamus can in turn impact CV reactivity through endocrine signals sent to the pituitary gland or neural signals sent to the medulla, where cells that drive sympathetic and parasympathetic activity are located. However, it is of note that CV reactivity can also be determined and regulated by many different complex processes (Saper, 2002).

A review of early work that included more than a hundred studies using positron emission tomography imaging during cognitive performance showed a consistent activation in the dACC in response to variations in task difficulty (Paus et al., 1998). Later on, further studies showed that dACC supports the generation of associated autonomic states of CV arousal during effortful cognitive processes (Critchley et al., 2005, 2003). Therefore, converging evidence supports the idea that autonomic activity is strongly influenced by dACC activity during cognitive performance.

However, psychological mechanisms underlying dACC activity are not completely understood (Radulescu et al., 2015). Cognitive interpretations of dACC function (as in the present integration) are predominant, but it was also proposed, for instance, that the function of the dACC may instead be to mediate the generation of autonomic bodily response used as afferent feedback through interoception to initiate or facilitate behavior execution (Critchley, 2004; Critchley and Harrison, 2013). In other words, 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. Moreover, 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. Therefore, the present integration aims to offer some ideas on these issues by considering research on the concept of cognitive control and on one cognitive interpretation of dACC function, both of which are presented in detail in the next section.

2. 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, cognitive control can be associated with effortful mental processes with the idea that controlled processes require effort, whereas automatic or habitual responses do not. This assumption is rooted in dual-process models that distinguish these two kinds of processes, i.e. automatic vs. controlled processes (Norman and Shallice, 1986; Posner and Snyder, 1975; Shiffrin and Schneider, 1977).

Dual-process models suggest that some cognitive processes and behaviors are performed in an automatic way, i.e. unintentionally and without effort, whereas other processes require some control and some effort. Automatic processes can be conceptualized as direct reactions to the environment driven by bottom-up processes and stimulus-response associations, which can be innate or learned through practice and experience (see Miller & Wallis, 2009). Numerous studies supported the idea of automaticity in behavior (Bargh and Chartrand, 1999), which represents a crucial aspect for survival, given the huge amount of information individuals have to process in their environment. The present integration therefore considers that individuals achieve a very large part of their goals or activities in an automatic way. However, in some situations, automatic behaviors are insufficient to sustain behavior, and individuals might exert some control and effort to sustain goal pursuit. The question then is how psychological and neural processes determine when, how much, and how long control and, in turn, effort should be implemented.

2.1. Conflict Monitoring and Control Implementation

The conflict-monitoring theory was proposed to address the issue of the initiation, modulation, and withdrawal of cognitive control (Botvinick et al., 2001). Previously, most theories focused on the nature of the influence exerted by control, but it was not clear how the system determines when and how much control is required. The conflict-monitoring theory proposes that cognitive control is initiated and modulated by a system that monitors for the occurrence of conflict in a given situation, which determines further compensatory adjustments. Furthermore, this theory integrated brain data that suggested that conflict detection is assumed by one particular area of the brain, the anterior cingulate cortex (ACC), which was later more precisely described as the dorsal anterior cingulate cortex (dACC). In previous research, the dACC was proposed to play a crucial role in cognitive control but its function remained unclear. The validity of this theory was first supported with regard to a large amount of previous evidence and also using computational modeling studies (Botvinick et al., 2001). Previous studies showed that dACC activity was associated with response override (e.g. Stroop task, flanker task, Simon task, go/no-go paradigm), undetermined responding (e.g. stem-completion task, verb generation task), and error commission, and that dACC activation in each of these contexts could be explained by the function of detecting conflicts.

Further research confirmed a dissociation between conflict monitoring associated with the dACC and implementation of control associated with other brain regions, especially the dorso-lateral prefrontal cortex (Egner and Hirsch, 2005; Kerns et al., 2004; MacDonald et al., 2000; Matsumoto and Tanaka, 2004). Implementation of control refers to the execution of controlled behavior through the engagement of cognitive processes that allow adapting and changing of automatic behavior. In this context, other research found that the DLPFC, and more broadly the lateral prefrontal cortex, is typically associated with executive functions, a set of basic cognitive functions (inhibition, switching, and updating) that are expected to be at the core of (almost) all controlled processes (Jurado and Rosselli, 2007; Miller and Cohen, 2001; Miyake et al., 2000; Niendam et al., 2012). Therefore, this line of research proposes that one process associated with the dACC is responsible for determining when and how much control has to be implemented on the basis of a conflict monitoring function, while a second process associated with more lateral prefrontal areas is responsible for executing this control—i.e. to get work done.

The precise mechanisms of controlled processes and dACC function are still not completely understood, with different hypotheses being suggested and many questions remaining open. A recent development of the conflict monitoring hypothesis, the EVC model (Shenhav et al., 2013), proposes an integrative account to describe dACC function in more detail. Only the important aspects of the model for the present integration are described here.

First, the EVC model added to the conflict-monitoring hypothesis a motivational component related to incentive, reward, and needs satisfaction, as well as potential threat associated with a given task or situation (Botvinick and Braver, 2015). These valuation processes are predicted to be processed by areas other than the dACC such as the insula, the ventral prefrontal cortex, the amygdala, the striatum, or the midbrain. Moreover, conflict monitoring is also expected to be influenced by the estimated cost of a given control, including the intrinsic cost of cognitive control itself (Kool and Botvinick, 2014), which is predicted to be evaluated in lateral prefrontal areas, i.e. different areas from those for value processing.

The model proposes that in addition to conflict monitoring, the function of the dACC is to integrate information about value and costs associated with potential controlled processes. This integration is expected to rely on the estimation of the net value associated with allocating control to a given task—a quantity labeled as the expected value of control (EVC). The output of this estimation determines whether it is worth investing control in a task, what kind of control should be exerted, and how much control should be implemented, i.e. the intensity of control. The model suggests that the amount of allocated control is driven by a cost-benefit analysis that integrates expected costs and potential payoffs. According to the authors, the EVC model can explain the diverse array of findings concerning dACC function.

From the perspective of the present integrative approach, this model includes several interesting propositions. First, it makes predictions on the intensity of required and justified control, which can be related to the notion of intensity of behavior, i.e. effort, proposed in motivational intensity theory. It is of note that the EVC model also considers the specification of the kind of control that will be implemented, but the present integration focuses only on the intensity aspect of the EVC model. Second, it takes into account task difficulty and success importance—the two key variables in motivational intensity theory—in the determination of required and justified control. Finally, it proposes distinct brain regions associated with processing information about task difficulty, success importance, and their integration, as well as with the execution of controlled processes. In other words, it provides a structure and organization of the mechanisms and brain areas underlying effortful controlled processes.

The following section describes the present integration, which aims to consider how effort-related CV reactivity might be associated with this structure and organization of controlled processes.

3. The Present Integration

Together, the previously presented lines of research led to the following conceptualization of psychological and neural processes underlying effort-related CV reactivity. Automatic cognitive processes handle most of our goals and activities until the organism detects that controlled processes are necessary to adjust ongoing behavior (Shiffrin and Schneider, 1977). This detection is achieved by the dACC, which monitors potential conflict in behavior adjustment and determines when and how much control is required (Botvinick et al., 2001). To do so, the dACC integrates information about value related to rewards and benefits, as well as potential threat in a given situation, which is processed in areas such as the insula, the ventral prefrontal cortex, the amygdala, the striatum, or the midbrain (Shenhav et al., 2013). Moreover, the dACC integrates information about costs associated with the situation, which is processed by lateral prefrontal areas. Cost evaluation includes information about costs of the controlled process itself (Kool and Botvinick, 2014), which should also be influenced by the current state of the individual regarding his or her ability to exert control (for instance, whether the individual is tired or not). In motivational intensity theory terms, the present approach suggests that the dACC integrates information about success importance and task difficulty of a given situation. An important aspect, however, is that information on success importance and task difficulty are elaborated separately in different brain areas and then integrated together within the dACC.

Output of dACC integration then determines when and how much control should be implemented, which is achieved by lateral prefrontal areas that assume executive cognitive processing (MacDonald et al., 2000), but also jointly determines CV response associated with this behavioral adjustment (Critchley et al., 2003). Therefore, CV response is not expected to be a direct product of lateral prefrontal cortex and executive functioning, but rather a product of the dACC, reflecting the amount of required and justified control. Finally, conflict monitoring is expected to occur continuously during cognitive control to monitor performance of ongoing behavior and to consequently adapt control, e.g. engaging more or less control and effort, or disengaging. The present integration is illustrated in Figure 2.

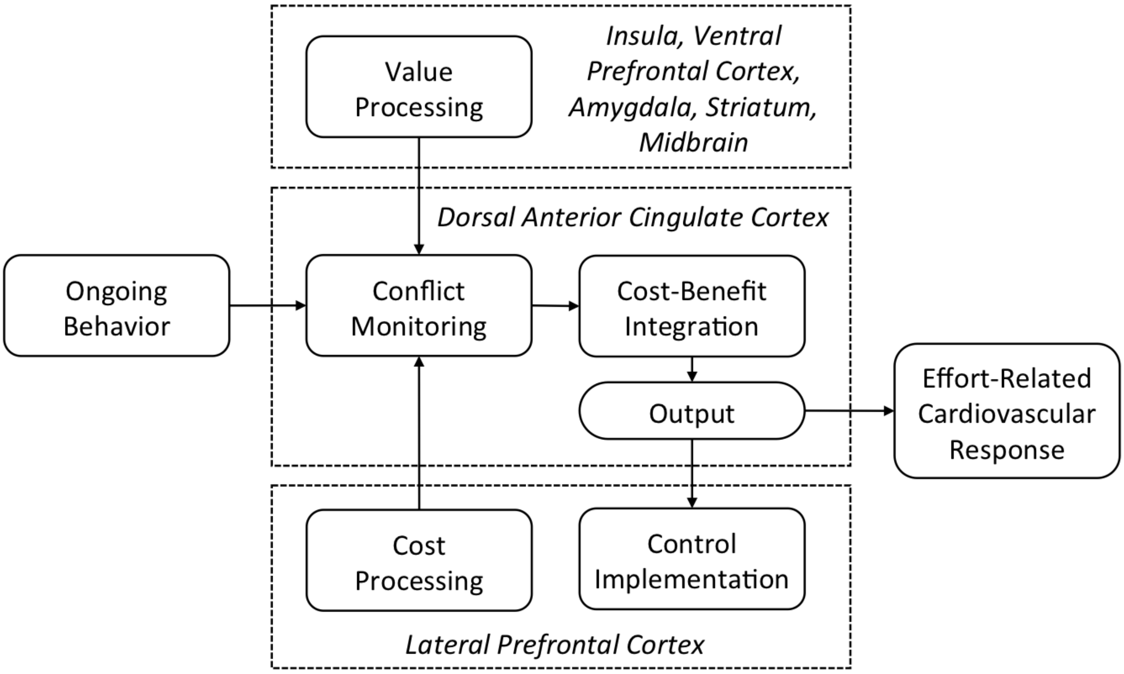

Figure 2. Illustration of the present integration.

3.1. Theoretical Implications

The present integration suggests that effort-related CV reactivity is determined by dACC output. This leads to a direct comparison between predictions of motivational intensity theory regarding CV reactivity and predictions of the EVC model on the intensity of dACC output. These attempts to compare theories are still preliminary and incomplete but it is hoped that they will inspire further research.

First, both models recognize that controlled processes are mostly determined with the aim of optimizing resource allocation and avoiding unnecessary waste. Motivational intensity theory proposes that individuals should not exert more effort than what is required, whereas the EVC model proposes that controlled processes should be “just strong enough to accomplish task objectives but not stronger" (Shenhav et al., 2013). Moreover, both models rely on similar determinants of the intensity of effort or control, i.e. task difficulty and success importance in motivational intensity theory, costs and payoffs in the EVC model.

However, there are important differences in how these models consider these determinants. For instance, the EVC model considers task difficulty to influence expected payoffs associated with a given controlled process. An increase in task difficulty is expected to reduce the probability of succeeding in the task and therefore the potential payoffs. More important, regarding the predictions, the EVC model predicts that dACC activity should increase with both task difficulty and task importance, which was supported by recent findings (Kouneiher et al., 2009). This suggests an additive effect of task difficulty and success importance. In contrast, motivational intensity theory proposes that task difficulty and success importance are independent factors that interact to determine effort intensity. Moreover, as presented earlier, this interaction depends on available information about task difficulty. A recent study integrated predictions of motivational intensity theory with cognitive control effects and the results suggested a nonlinear pattern, in line with the interaction effect (van Steenbergen et al., 2015). Therefore, these considerations suggest potential contradictions between these theories that may be addressed in future studies, as discussed later.

Finally, motivational intensity theory predicts that individuals should disengage from a task when required effort is not justified. This issue is not discussed in detail within the EVC model, but one may speculate that disengagement depends on the level of EVC attributed to controlled processes according to a certain threshold. When EVC is below a critical level, this should result in withdrawal and disengagement from the task. This issue would also be worth investigating in future studies.

3.2. Some Insights from the Present Integration

The first question that may be discussed in light of the present integration is whether CV reactivity is caused by engagement of cognitive resources, or by a process of peripheral activation that accompanies effortful cognitive processes. The integration suggests the second answer, given that CV reactivity is expected to be determined by the dACC (Critchley et al., 2003) rather than by lateral prefrontal areas, which are associated with control implementation, i.e. the engagement of executive functions. During task performance, CV response is expected to increase or decrease with implementation of control because the same output influences both CV response and control implementation regarding the amount of required and justified effort. Therefore, during task performance, CV response should reliably reflect control implementation and, in turn, effort, and this claim offers an additional rationale for the use of sympathetic CV measures as indicators of effort in the CV paradigm.

However, it is also important to acknowledge that CV reactivity is not a direct product of lateral prefrontal cortex and executive functioning. Rather, CV reactivity can be conceptualized as peripheral activation that is proportional to executive functioning and therefore to effortful cognitive processes. In the context of a definition of effort as the amount of resources people mobilize to carry out behavior (Gendolla and Wright, 2009), the present integration suggests that at least two types of resources are mobilized during cognitive tasks: resources related to the lateral prefrontal cortex and executive functions, and resources related to autonomic and CV reactivity. The question of the interaction between these types of resources, such as whether and how autonomic activity might initiate or facilitate executive functioning, remains a large issue to be investigated (Critchley, 2004; Critchley and Harrison, 2013).

A second point that may be addressed concerns anticipatory CV responses. Several studies have found different levels of CV reactivity, depending on anticipated task difficulty and task importance before the task started (e.g. Wright, Brehm, & Bushman, 1989; Wright, Brehm, Crutcher, Evans, & Jones, 1990). These findings were interpreted as showing that CV adjustments occur not only to sustain behavior, but also to prepare individuals for impending actions. Beyond this functional perspective, the question remains as to whether these CV adjustments reflect a kind of phenomena that is different from CV adjustments during task performance. In other words, does it make sense to claim that individuals are exerting effort before the task? The present integration suggests that individuals may determine the amount of required and justified effort regarding an upcoming task, which would proportionally increase CV reactivity. An important aspect is that this may happen before individuals have the opportunity to exert control through executive functions. In this situation, CV reactivity would reflect how much effort an individual is going to engage in a task even though he or she has not started to work on it. This argument does not exclude, however, that some preparatory control implementation may occur before the task. It is plausible that the processing on how to perform the task starts before the task itself in order to determine an optimal strategy to succeed—at least when some information about the task is available.

Finally, the relationship between CV reactivity and cognitive performance may be discussed in light of the present integration. In studies that use the CV paradigm, the pattern of results related to task performance, usually assessed as reaction times or accuracy, can be relatively different than that for CV reactivity (Chatelain et al., 2016). This difference is typically explained by using goal setting theory (Locke and Latham, 1990)), with the idea that performance does not depend on effort alone, but also on other factors such as ability or strategy. Accordingly, the determinants of performance are various and complex and effort does not always have a direct impact on it. In this context, a common striking finding in the CV paradigm relates to conditions in which disengagement (or at least a lower CV reactivity) is found in terms of effort while performance remains at a relatively high level (Silvestrini and Gendolla, 2013). How can the present integration explain this dissociation between CV measures of effort and task performance?

This dissociation might be related to the dissociation between automatic and controlled processes. Accordingly, one may expect that individuals are able to execute various tasks successfully by using automatic processes. When task difficulty increases and the outcome is sufficiently worthwhile, individuals may want to exert additional control, i.e. mobilize more effort, to increase the probability of succeeding in the task. However, in some situations, it might be the case that individuals are not prone to exerting effort—i.e. the output of the cost-benefit analysis does not justify effortful control—and they perform the task by using only effortless automatic processes. Here, the amount of required and justified effort is close to zero, which results in low CV reactivity, whereas automatic processes may still provide a rather good performance. This situation would therefore reflect a state in which individuals are not really concerned about the outcome of the task and rely on automatic processes to cope with it.

This explanation can also be related to the notion of the ability of each individual to successfully perform a task. Ability could be associated with efficiency of automatic processes on the one hand and with additional efficiency provided by additional effortful control on the other. A typical conception of ability and effort relates to the compensatory function of effort for individuals who have a low ability to achieve a task (Hockey, 1997; Wright and Dill, 1993). To attain a similar level of performance in a relatively easy task, low-ability individuals are expected to exert more effort than high-ability individuals. Therefore, effortful processes could be considered as compensating the lack of efficiency of the automatic processes that are reflected in interindividual variability in terms of ability. This issue can also be related to the notion of learning, i.e. how controlled processes can become automatic and how effortful activities may become effortless after we have acquired the necessary skills to master them.

3.3. New Predictions from the Present Integration

In addition to offering explanations for the previous results, how far can the present integration go in proposing new predictions? As discussed earlier, a first point to critically investigate would be the potential additive effect of task difficulty and success importance proposed by the EVC model, in contrast to the interactive effect proposed by motivational intensity theory. It may be the case that until a certain degree of success importance is reached, individuals rely only on task difficulty. But when success becomes more important, individuals might adjust and increase their effort according to success importance. The present integration at least suggests that individuals could do so, considering the predictions of EVC model. These predictions may be tested by assessing CV reactivity during a task with fixed and easy difficulty, together with three levels of monetary incentive: low (about $1), moderate (about $5), or very high ($50 or $100). The EVC model would predict that individuals engage more control with an increase in incentive. In contrast, motivational intensity theory would predict that individuals engage a similar level of effort in different incentive conditions as long as the required effort does not exceed the effort justified by success importance.

A second point worth investigating is related to the relationship between effort and performance. The integration proposes that controlled processes occur when automatic processes are insufficient to sustain behavior. From another perspective, controlled processes therefore occur to increase performance compared to that with automatic processes. Consequently, the effect of controlled processes and effort on performance should be more visible when task difficulty is sufficiently high, such as when automatic processes are not able to cope with the task efficiently. This prediction may be tested in an experiment by using a difficult switching task, such as the switching Stroop (MacDonald et al., 2000) together with the assessment of CV measures. Here, one would predict that additional effort increases performance, given that automatic processes should not be able to cope with task switching and performance should be related to additional control and, in turn, effort.

Finally, given that the present integration proposes brain areas associated with CV reactivity, functional magnetic resonance imaging (fMRI) studies may be performed to test the predictions of motivational intensity theory and the EVC model on the BOLD signal, together with assessment of CV reactivity. It is important to note here, however, that fMRI and CV measures both have constraints that may be limitative when integrating these measures together. First, experimental designs in fMRI studies are more sensitive when using short periods and a certain number of repetitions of the conditions. In contrast, CV measures as PEP or SBP are commonly assessed during relatively longer periods for physiological reasons. For instance, methodological guidelines suggest that PEP analysis requires the averaging of impedance cardiography signals for several heartbeats (Sherwood et al., 1990).

However, it is important to note that motivational intensity theory makes predictions about effort mobilization at a point in time. Although the theory's predictions are also applicable to single trials of a task, this approach has not been investigated to date. As a first step in this approach, a recent study that included a new method to assess CV reactivity at a single-trial level offered promising perspectives (Kuipers et al., this issue). Second, assessing PEP with impedance cardiography implies induction of a light current through the body of the participant that may interact with the MRI environment. Only recently, a study showed that impedance cardiography can be used during MRI (Cieslak et al., 2015)), suggesting promising new methods to compare the predictions of motivational intensity theory and the EVC model.

3.4. Extending the Integration to Self-Regulation

Some evidence suggests that controlled processes and the dACC may be more broadly associated with the concept of self-regulation, which is related to how individuals adapt their behavior when confronted with different types of situations. A recent review revealed converging evidence that the dACC—termed the anterior mid cingulate cortex, aMCC—is associated with cognitive control, as well as with two other self-regulatory processes: pain and negative affect regulation (Shackman et al., 2011). This review suggests that the basic mental processes engaged in cognitive control during a cognitive task—i.e. executive functions (inhibition, switching, updating)—are also responsible for the regulation of thoughts, emotions, and behaviors associated with pain and negative affect. The authors proposed an “adaptive control hypothesis” related to the function of the dACC in these self-regulatory processes. According to this view, the dACC implements adaptive control by integrating information about punishment to determine an optimal course of action in the face of uncertainty. Interestingly, several years earlier, Kahneman (Kahneman, 1973) recognized that the ability to flexibly adapt behavior to current task demands was an important aspect of cognitive control. Together, these findings suggest that the integration of value and costs associated with control implementation may be a common mechanism in self-regulation.

Following the rationale of dual-process models (Shiffrin and Schneider, 1977), the role of controlled processes in self-regulation may be conceptualized as voluntary and effortful top-down influence on automatic bottom-up responses (see Hofmann, Schmeichel, & Baddeley, 2012). This idea has received some support in the domains of emotion regulation (Ochsner and Gross, 2008), pain regulation (Bushnell et al., 2013; Legrain et al., 2009; Lorenz et al., 2003; Wiech et al., 2008), and cognitive control (MacDonald et al., 2000).

This perspective may also be extended to physical effort, with the idea that psychological and neural processes associated with cognitive control drive physical effort. Indeed, previous research suggests that exercise performance is mainly limited by the perception of effort rather than by physiological factors (Marcora et al., 2009). Moreover, interestingly, several neuroimaging studies suggest that the ACC, together with portions of the insular cortex, works as a central command network during physical exercise, functioning to interpret an individual’s sense of effort and then eliciting appropriate autonomic adjustments to affect CV responses (Williamson et al., 2006). In this context, it may be noted that automatic muscle activity (e.g. digestion) is sometimes considered to require effort in the literature on physical activity. However, this point mainly reveals definition issues related to the construct of effort that is often different in various domains. According to the present integration, effortful processes are related to situations in which individuals have some control of the outcome of a situation—i.e. active coping (Obrist, 1976). Therefore, given that automatic muscle activity is usually not controllable, considering automatic physical activity as effortful is debatable. But this issue deserves further clarification and discussion that should be developed in the future.

4. Conclusion

The present integration aimed to advance our understanding of the psychological and neural processes underlying effort-related CV reactivity. Overall, the integration provides a theoretical framework that describes how individuals detect when and by how much controlled processes should be engaged, how information on task difficulty and success importance is processed, and which brain areas are associated with these processes and the production of CV reactivity. 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.

An important point, however, is that information on task difficulty and success importance is expected to be first processed in different brain areas other than the dACC—the insula, ventral prefrontal cortex, amygdala, striatum, and midbrain for success importance; the lateral prefrontal cortex for task difficulty—and then integrated by the dACC to determine the intensity of controlled processes. Moreover, evidence indicates that executive cognitive functioning is also processed in brain areas other than the dACC, namely in more lateral regions of the prefrontal cortex. Therefore, the present integration suggests that CV reactivity is not a direct product of lateral prefrontal cortex and executive functioning. However, effort-related CV reactivity can be conceptualized as peripheral activation that is proportional to executive functioning and therefore to effortful cognitive processes. Many questions remain, but it is hoped that the present attempt will stimulate new predictions and ideas to help deepen the understanding of effortful processes.

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