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Patterns of brain and cardiovascular activation while solving rule-discovery and rule-application numeric tasks

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ABSTRACT

It is known that solving mental tasks leads to tonic increase in cardiovascular activity. Our previous research showed that tasks involving rule application (RA) caused greater tonic increase in cardiovascular activity than tasks requiring rule discovery (RD). However, it is not clear what brain mechanisms are responsible for this difference. The aim of two experimental studies was to compare the patterns of brain and cardiovascular activity while both RD and the RA numeric tasks were being solved. The fMRI study revealed greater brain activation while solving RD tasks than while solving RA tasks. In particular, RD tasks evoked greater activation of the left inferior frontal gyrus and selected areas in the parietal, and temporal cortices, including the precuneus, supramarginal gyrus, angular gyrus, inferior parietal lobule, and the superior temporal gyrus, and the cingulate cortex. In addition, RA tasks caused larger increases in HR than RD tasks. The second study, carried out in a cardiovascular laboratory, showed greater increases in heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP) while solving RA tasks than while solving RD tasks. The results support the hypothesis that RD and RA tasks involve different modes of information processing, but the neuronal mechanism responsible for the observed greater cardiovascular response to RA tasks than to RD tasks is not completely clear.

1. Introduction

Although it is known that mental task solving leads to tonic increases in cardiovascular activity, the explanation for these increases is by no means obvious. These changes cannot be explained as a response to present or anticipated increases in the brain's energy expenditure because solving mental tasks does not lead to an increase in global cerebral metabolic rate (cf. Madsen et al., 1992; Sokoloff et al., 1955). The energy expended by the entire organism can, of course, vary widely, especially during physical effort, and the cardiovascular system can precisely adapt to these changes (cf. Brener, 1987; Requin et al., 1991). However, during psychological stress, tonic cardiac activity can increase above the level expected for the expenditure of energy (Blix et al., 1974; Sherwood et al., 1986; Carroll et al., 1986). The phenomenon of metabolically exaggerated cardiac activity is understandable when it accompanies preparation for metabolically costly motor actions (cf. Requin et al., 1991; Magel et al., 1969; McArdle et al., 1967). However, it remains unexplained during mental task solving that does not demand substantial physical effort. According to many authors, cardiovascular changes observed during mental task solving may be interpreted as indices of active coping (cf. Obrist, 1976). However, this concept is not entirely clear and has been subject to various interpretations. According to Brehm and Self (1989) cardiovascular changes during mental task solving can be treated as an index of motivational arousal, meaning the “total amount of effort a person would make to satisfy a motive” (p. 110). Wright (1996) argues that “effort effects are likely manifested within a system whose function is directly related to the energy mobilization process, i.e., cardiovascular system” (p. 425). Numerous studies have shown that Brehm and Wright's theory predicts well cardiovascular changes during mental task solving. In particular, when task difficulty is fixed and required effort is justified by the motive (cf. Richter and Gendolla, 2007; Wright

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et al., 2002), the shortening of the pre-ejection period (PEP) and increases in heart rate (HR) and systolic blood pressure (SBP) are usually a curvilinear function of task difficulty (Richter et al., 2008; Obrist et al., 1978). When task difficulty is unclear or can be chosen by the performers themselves, the changes in PEP, HR and SBP are a linear function of incentive value (Fowles et al., 1982; Richter and Gendolla, 2009). However, the biological reason for this mobilization of the cardiovascular system remains unclear. Some recent studies have suggested that the perceived effort accompanying mental task solving is not the outcome of increased energy expenditure but rather the side effect of cognitive and motivational processes (cf. Hockey, 2013; Kurzban et al., 2013).

Another problem is the specificity of the cardiovascular responses to various task demands. There are two basic modes of task coping, one involving the performance of previously learned actions and the other involving problem solving (cf. Cooper and Shallice, 2000; Duncan, 1986; Jeannerod, 1997; Norman and Shallice, 1986; Shallice, 1988). This distinction corresponds to the concept of two modes of information processing: *rule application (RA)* and *rule discovery (RD)*. Our previous research has shown that these modes of information processing affect cardiovascular responses to mental task solving. The research used two types of mental tasks of the same difficulty (cf. Sosnowski et al., 2004). One of them, the RUN task, required performing ready-to-use programs, including arithmetic operations, and the other, the EDIT task, required searching for the solution to a problem, including logically completing a series of digits. The results showed that RUN tasks, in comparison to EDIT tasks, caused greater increases in HR (Sosnowski et al., 2004), SBP, diastolic blood pressure (DBP), and mean blood pressure (MAP) (Sosnowski et al., 2010) and greater shortening of the PEP (Sosnowski et al., 2012). The effect of RUN/EDIT tasks has been demonstrated in a variety of tasks, including numeric, verbal, and two-dimensional figure tasks (Sosnowski et al., 2004). Our previous research also suggests that the difference in cardiovascular response to RUN and EDIT tasks is due to the difference in activation of the sympathetic (beta-adrenergic) nervous system, while vagal influences on the heart do not differ between the two types of tasks (Sosnowski et al., 2012).

The problem is identifying which factors are responsible for the differences in cardiovascular reactivity between the two types of tasks. Our previous results led to the conclusion that the increase in cardiovascular activity is greater if the subject knows the action program that is to be executed. If the action program is not known, and the task requires searching for the appropriate program, motivational arousal and mobilization of the cardiovascular system are lower. This does not mean, of course, that problem solving does not demand mental effort or task engagement. Rather, the results suggest that the two types of tasks involve qualitatively different information processing and different motivational processes. If this is so, one can expect that each type of task would evoke a different pattern of brain activation.

Numerous studies using various types of RD and RA tasks similar to RUN and EDIT tasks seem to agree with our expectations. Shallice and coworkers (Norman and Shallice, 1986; Shallice, 1988) showed that patients with frontal-lobe lesions are able to correctly perform tasks that require using well-learned skills in a routine fashion, for example, the digit-span subtest of the Wechsler Adult Intelligence Scale (WAIS), whereas their performance is extremely poor when novel programming of external or internal action sequences is required, for example, while solving tasks including the Block Design subtest of the WAIS, the Wisconsin Card Sorting Test (WCST), and the Tower-of-London (Norman and Shallice, 1986; Shallice, 1988).

In addition, numerous brain-imaging studies (Berman et al., 1995; Bunge, 2004; Ragland et al., 1997; van den Heuvel et al., 2003) have demonstrated that solving RD tasks leads to increased activation of the prefrontal cortex (PFC) and selected areas in the parietal, temporal, and occipital cortices. It has also been shown that the PFC is activated more strongly while solving RD tasks than while solving RA tasks. For example, Crescentini et al. (2011) found enhanced activation of the mid-dorsolateral PFC during the rule-search and RD task phase, whereas the temporal, motor, and medial/anterior PFCs were more strongly activated during the rule-following phase. Liu et al. (2015), using a task similar to the WCST, showed that rule learning, in comparison to RA, more strongly activated the middle superior and inferior frontal gyrus and the anterior insula.

In their research with WCST, Somsen et al. (2000) found that a rule search leads to short-lasting cardiac deceleration, whereas rule application leads to cardiac acceleration. They also suggested that frontal/septo-hippocampal pathways may inhibit cardiac activity during rule search.

Critchley et al. (2000) demonstrated that increased heart rate and mean arterial pressure during effortful isometric exercise and mental arithmetic are associated with enhanced activation of the cerebellar vermis, brainstem, and right anterior cingulate, whereas activation of the amygdala and insula was greater during control than stress conditions. However, other research (Critchley et al., 2003) indicated that damage to the ACC region had limited effects on neuropsychological performance (including mental arithmetic), what suggests that “the ACC may fulfill a rather limited role in general attentional or executive control of cognitive functions” (p. 2149). In a later paper, Critchley et al. (2011) suggested a more complex relationship between ACC and the autonomic nervous system: “[…] cortical activity in regions including anterior/mid cingulate cortex and bilateral insulae are linked to autonomic arousal accompanying a variety of behavioural tasks and processes that typically require effort and behavioural engagement with external stimuli. Dorsal anterior/mid cingulate particularly reflects sympathetic effects in the periphery, while ventromedial prefrontal cortex and subgenual cingulate negatively reflect sympathetic tone and may also reflect effects mediated parasympathetically” (p. 37). However, assessment of sympathetic and parasympathetic influences on cardiovascular responses during psychological stress is a complex problem because these influences do not have to be reciprocal (Berntson et al., 1994).

Although the data presented above are not completely consistent, they suggest that EDIT tasks, in comparison to RUN tasks, should evoke greater increases in activation of the PFC and selected areas of the temporal, parietal, and occipital cortices. The pattern of brain activation specific to RUN tasks is more difficult to predict, although some studies suggest that these tasks can lead to decreased activation of the PFC and increased activation of some subcortical areas responsible for cardiovascular activation.

The aim of the current study was to compare the patterns of brain and cardiovascular activity while subjects solved RUN and EDIT numeric tasks of the same objective and perceived difficulty. In Experiment 1, we analyzed changes in brain activity and heart rate responses while solving both types of task in an fMRI scanner. In Experiment 2, we assessed the effects of the same tasks on the cardiovascular variables that could not be registered during the fMRI procedure. Analysis of both experiments aimed to answer the question of whether the expected differences in cardiovascular responses to RUN and EDIT tasks were associated with differences in brain activity.

2. Experiment 1 – fMRI study

2.1. Introduction

The aim of Experiment 1 was to compare changes in brain activity and tonic HR while subjects solved RUN and EDIT numeric tasks. Brain activity was assessed using fMRI, and HR changes during the magnetic resonance procedure were measured by infrared pulse oximeter. In line with the results of our previous research, we expected greater HR increases while solving RUN tasks than EDIT tasks. However, the most important question concerned the differences in brain activation while solving both types of tasks.