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Mental engagement during cognitive and psychomotor tasks: Effects of task type, processing demands, and practice

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ABSTRACT

Measures of heart rate variability (HRV) are hypothesized to provide indices of mental engagement (ME). HRV and perceived workload were measured to determine whether ME is moderated by task type, processing demands, and practice. Twenty four (22 ± 3 yrs.) participants were assigned to groups that performed either two executive-processing (EF) tasks or two non-executive processing (NEF) tasks. Across 3 sessions, participants practiced a cognitive computer-based cognitive task and a psychomotor task. HR was recorded for 5-min epochs before and during each task; workload ratings were recorded following each task. ANOVAs revealed that participants' HRV decreased when performing cognitive and psychomotor tasks; the decline was greater, however, for NEF tasks. Over sessions, HRV increased during EF but not NEF tasks; workload scores lessened during EF but not NEF tasks. ME was intensified when participants learned novel cognitive and psychomotor tasks; however, the intensity level depended on the task, and its maintenance was altered with practice.

1. Introduction

Mental engagement (ME) has been a central explanatory construct in a number of theories of human performance (Hockey, 1997; Wickens, 2008), child development (Christenson et al., 2012), and aging (Hess, 2014). In these research domains, ME is conceptualized as a motivational variable that influences an individual's willingness to allocate effort and resources to acquire conceptual ideas or skills (Mahatmya et al., 2012; Wright and Gendolla, 2012). Measures of physiological activity and self-report are often used as convergent evidence for the impact of specific conditions on an individual's task-related mental engagement (Hess, 2014).

For more than a century, researchers have studied changes in autonomic nervous system activity that occur when individuals are affected by environmental stressors or during task performance (Thayer and Lane, 2009). Indices of heart rate variability (HRV), because of its ability to describe the interplay between sympathetic and parasympathetic activation, have been viewed as a direct measure of brain-heart integration that underlies behavior (Thayer et al., 2012). A growing literature links bi-directional neurological pathways from the frontal cortex of the brain to sympathetic and parasympathetic divisions of the autonomic nervous system (ANS) (see Riganello et al., 2012 for a review). The Central Autonomic Network (CAN) provides a model that helps explain how goal-directed behaviors are mediated by descending projections from the prefrontal cortex to subcortical nuclei that modulate cardiovascular activity, and by ascending projections from brainstem autonomic structures that influence subcortical and cortical structures. The CAN model and evidence of the relation among multiple neural networks have led Thayer et al. (2009)) and others (Hess, 2014) to propose that measures of HRV and ANS activation may serve as indices of changes in mental processing that occur when individuals perform tasks that involve the allocation of attention and mental engagement.

Similarly, measures of subjective physical and mental workload have been used to assess the impact of stressors on human performance (Hart, 2006; Hockey, 1997). Central to general theories of workload (e.g., Hockey, 1996, 1997) is the notion that the demands individuals face when new learning tasks lead to alterations of the ANS in ways that prepare the individual for action; however, the intensity of the physiological response pattern can be modulated by conscious cognitive processes. Several studies have reported concomitant changes in learners' reports of subjective workload and indices of ANS activity as a function of task demand (Miyake, 2001; Ryu and Myung, 2005) and practice (Haga et al., 2002).

Hypotheses generated from the CAN model concerning ME have been supported in several studies that investigated the modulation of vagally mediated cardiac function during periods of rest and during cognitive task performance. For example, Hjortskov et al. (2004) reported a reduction in the high-frequency HRV component in young women performing a random-number generation computer task, compared to rest. Tripathi et al. (2003) obtained 5-min spectral HRV measures of young adults prior to and during performance of tests of attention,

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stimulus discrimination, and working memory, each of which varied in level of cognitive demand. Compared to baseline levels, significantly lower measures of normalized HF/LF ratio HRV values were observed only during tests of working memory. The magnitude of HRV change did not differ as a function of mental load. More recently, Taelman et al. (2011) provided evidence that the magnitude of ANS responses increases as mental demand increases. They assessed 6-min recordings of young adults' HRV under a rest condition, a visual stimulus-detection task (low demand), and a mathematics computation task (high demand). Both task conditions resulted in lower vagal modulation; however, the effect was significantly greater under high demand conditions. These findings suggest that the relation between HRV and ME may be task specific and driven by the level of the task's mental demands.

Cognitive tasks are often categorized two ways: those that draw upon executive functions (EF), which involve planning, switching, and updating, and those that do not involve executive functioning (NEF), such as stimulus identification and choice discrimination (Miyake et al., 2000). Recently, researchers have explored the possibility that vagal regulation may be more closely associated with EF rather than NEF processing (Mathewson et al., 2011). Luft et al. (2009) compared time and frequency indices of HRV in highly physical fit young adults during rest and while performing a battery of cognitive tests. Participants' normalized LF/HF ratios differed from rest conditions only when performing two memory-demanding tests and did not differ from rest when performing simple-RT, choice-RT, and monitoring tests. However, Luque-Casado et al. (2013)) assessed high- and lower-physically fit young adults' HRV during a 6-min baseline period and during an attentionally demanding stimulus-identification task, an EF temporal orienting task, and a NEF psycho-physical temporal discrimination task. For both fit and less-fit individuals, lower time-domain HRV measures were obtained only during the temporal discrimination task, which required participants to make subtle discriminations between stimuli. The authors suggested that the perceptual demands of the task were driving mental engagement. Thus, it is unclear whether alteration of HRV is driven by higher-order executive processes, by specific types of attentional-demanding perceptual discrimination processes, or both.

The present study evaluated young adults' ME during the performance of cognitive and psychomotor tasks differing in their degree of executive control. The selection of EF and NEF tasks in each category was based on methods described by Kramer et al. (2002). A computer generated maze-learning task and a bi-manual star-tracing task were selected as cognitive and psychomotor EF tasks, respectively. These tasks were characterized by conditions that provided learners with controlled top-down processing and the ability to employ response-produced feedback to guide their actions. A computer generated visual-discrimination task and a motor tapping task were selected as cognitive and psychomotor NEF tasks, respectively. These tasks were characterized by conditions that imposed rapid perceptual decision-making demands or movements. Over three practice sessions, participants' HRV, subjective ratings of task workload, and task performance were assessed. These indices were hypothesized to change as predicted by general theories of skill acquisition (Ackerman, 2014; Fitts and Posner, 1967; Proctor et al., 1990), with alteration of HRV and reduced workload ratings occurring for all tasks with practice. Based on the CAN model and prior studies (Mathewson et al., 2011), the EF tasks performed in the present study were predicted to elicit greater mental engagement than the NEF tasks and that these differences would remain over multiple practice sessions.

2. Method

2.1. Participants

Twenty-four participants ($M = 21.9$ yrs., $SD = 3.03$, range = 18–31, 75% F) were recruited from classes at the University of Georgia. Each participant read an Institutional Review Board approved consent form that described the procedures and rationale for the experiment. Following agreement to participate, the participant was asked to complete a demographic information form, a health form, and an exercise habits questionnaire (Godin and Shephard, 1985). Heath history data collected revealed that none of the participants had major health problems. One participant indicated never participating in leisure time physical activity, 33.3% of participants engaged in activities 1–2 times per week, and 62.5% engaged in activities 3 or more times per week. Total Godin Leisure-Time Exercise Questionnaire scores ($M = 58.65$, $SD = 20.02$) characterize participants as highly physically active. All volunteers met the inclusion criteria for the study.

2.2. Group assignment and procedure

Participants were randomly assigned either to a group which practiced two tasks that required EF (n = 11; F = 9) or to a group which practiced two tasks that did not impose EF (n = 13; F = 9). Participants agreed to be tested individually and to complete three 60-min sessions at the same time of day. As part of the first session, each participant was given detailed information regarding ECG recordings, testing procedures, and how to interpret and score individual items of the NASA-TLX workload-rating instrument (described below). Each session consisted of a series of stages. First, the participant completed a 24-hour diet and physical activity recall questionnaire. Next, the participant entered a test chamber and was asked to sit in front of a computer monitor placed on a table. Once seated, electrodes were placed in a 3-lead configuration around the heart with 3 electrodes on the chest and a fourth grounding electrode attached to the inner right ankle. ECG data were recorded continuously throughout each session. The participant was instructed to remain seated quietly for 5 min, which afforded baseline HRV measurement. The participant was then instructed to initiate one of the two cognitive computer-based tasks (described below), which lasted 5 to 7 min and involved decisions and responses made via button presses on a standard computer mouse. Following the cognitive computer-task, a researcher instructed the participant to complete a TLX workload form and then to sit quietly for 5-min. The researcher then replaced the computer monitor with one of the two psychomotor test apparatus (described below) and provided instructions. The participant practiced the task for approximately 5 min and was then instructed to stop, complete a TLX workload form, and then sit quietly for 5 min. At the termination of the session, the participant confirmed the next appointment or was debriefed if it was the last day.

2.3. Test instruments

2.3.1. Workload assessment

The NASA-Task Load Index (TLX) (Hart and Staveland, 1988) was used to assess subjective workload. The TLX is a standardized multidimensional subjective rating scale and one of the most widely used mental workload assessment instruments techniques used in human factors research (Hart, 2006; Hill et al., 1992). Using a 50-mm visual-analog scale (VAS), participants rated six factors: mental workload, mental effort, physical demands, temporal demands, performance, and frustration. Participants placed a pencil mark on each line, the distance of which was measured following the session and recorded by a researcher. An overall workload measure was calculated from the sum value of all six subscales.

2.3.2. Executive function tasks

2.3.2.1. Groton maze learning. The EF maze tasks required spatial problem solving. A grid was displayed on a computer monitor and controlled by a commercial software program (CogState Research Manual, 2009). A blue tile at the top left of a grid indicated the maze start and a red tile at the bottom right grid indicated the goal. The participant navigated the maze one tile at a time by placing a cursor on a tile and clicking a