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Autonomic regulation and maze-learning performance in older and younger adults

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ABSTRACT

There is growing evidence that centrally modulated autonomic regulation can influence performance on complex cognitive tasks but the specificity of these influences and the effects of age-related decline in these systems have not been determined. We recorded pre-task levels of respiratory sinus arrhythmia (RSA; an index of phasic vagal cardiac control) and rate pressure produce (RPP; an index of cardiac workload) to determine their relationship to performance on a cumulative maze learning task. Maze performance has been shown to reflect executive error monitoring capacity and non-executive visuo-motor processing speed. Error monitoring was predicted by RSA in both older and younger adults but by RPP only in the older group. Non-executive processes were unrelated to either measure. These data suggest that vagal regulation is more closely associated with executive than nonexecutive aspects of maze performance and that, in later life, pre-task levels of cardiac workload also influence executive control.

1. Introduction

Heart rate, or its inverse, the interbeat interval (IBI) is the net outcome of the competing innervation of the heart by the sympathetic and parasympathetic nervous systems at the sino-atrial node, i.e., the heart's pacemaker (e.g., Cacioppo et al., 1994). The activity of the pre-ganglionic sympathetic and parasympathetic neurons that drive the heart's pace-maker is modulated by a network of midbrain and cortical structures, including the insular cortex, anterior cingulate cortex (ACC), ventromedial prefrontal cortex, the central nucleus of the amygdala, and the hypothalamic nuclei (e.g., Benarroch, 1997; Critchley et al., 2000; Ter Horst and Postema, 1997). This central modulation of autonomic influences is reflected in measures of respiratory sinus arrhythmia (RSA), a natural irregularity in the cardiac signal related to the respiratory cycle that is commonly used to index phasic changes in cardiac vagal control (Berntson et al., 2007). In this model, higher resting levels of RSA are associated with increased physiological flexibility and behavioral adaptability. Thus, variation in the interval between heart beats is considered by many to be a hallmark of adaptive physiological regulation (e.g., Beauchaine, 2001; Porges, 1995a; Thayer et al., 2009).

Like many other regulatory functions, autonomic control declines substantially with age (e.g., DeMeersman and Stein, 2007; Umetani et al., 1998) and this reduction appears to be greater for parasympathetic than sympathetic regulation (Korkushko et al., 1991). Differentially reduced parasympathetic control results in less variability in the cardiac signal and shifts the relative balance between the two branches of the autonomic nervous system toward greater sympathetic predominance (Korkushko et al., 1991; Singh et al., 2006) so that physiological aging results in a mild form of autonomic dysregulation.

Whereas RSA is used to reflect central influences on cardiac control, rate pressure product (RPP, systolic blood pressure × heart rate/100) provides an indirect assessment of myocardial oxygen consumption (Gobel et al., 1978) and reflects current cardiac workload. Specifically, RPP represents the maximum pressure in the ventricle when it is ejecting blood multiplied by the number of beats per minute. In the resting state, it is most adaptive for levels of RPP to be low but during the performance of challenging tasks RPP will increase indicating that myocardial oxygen consumption has risen from resting levels to meet the metabolic requirements of the new activity (Fredericks et al., 2005). RPP is reported to increase during exercise (Fredericks et al., 2005; Robinson, 1967), every-day physical activity (Atkinson et al., 2009) and psychological stress

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(e.g., Fredericks et al., 2005; Merritt et al., 2004). RPP is also positively correlated with risk for silent myocardial ischemia (Atkinson et al., 2009; Deedwania and Nelson, 1990) and has served as an index of treatment response in those with hypertension (White et al., 1998; White, 1999). If RPP is high in the resting state, we could assume that myocardial oxygen use is already elevated in the absence of significant metabolic demands.

Our question was whether these indicators of cardiac function would allow us to predict cognitive performance over and above any variance associated more generally with age. Flexible and efficient autonomic regulation (reflected in high levels of RSA) has been positively associated with executive functioning as demonstrated in the performance of working memory and sustained attention tasks in young adults (Hansen et al., 2003, 2009; Johnsen et al., 2003), older adolescents (Di Bernardi Luft et al., 2009) and children (Seuss et al., 1994; Staton et al., 2009). In contrast, performance on simpler tasks that do not appear to demand executive skills have been associated with steady, faster heart rates and reduced variability (e.g., Di Bernardi Luft et al., 2009; Duschek et al., 2009). These differential outcomes suggest that parasympathetic influence in autonomic control may be most important for tasks that evoke executive skills, and less important for those that elicit non-executive processes. Thus, our first goal was to ascertain the degree to which central modulation of autonomic regulation and cardiac workload (measured by RSA and RPP, respectively) were related to executive versus non-executive aspects of task performance.

We were also interested in the effects of aging on the relationship between autonomic regulation and executive function. It is well established that executive functions decline with age (e.g., Gazzaley and D'Esposito, 2007; Prakash et al., 2009). Processes such as the selection and maintenance of goals and the suppression of prepotent response tendencies are generally found to be less efficient in older adults (Good et al., 2001; Pardo et al., 2007; Vaidya et al., 2007; West, 1996). What is not known, however, is whether declining control over autonomic regulation contributes to age-related decline in executive functioning. Therefore, more specifically, we wanted to determine whether pre-task levels of autonomic regulation contribute to age-related decline in executive relative to non-executive function over the general effects of age itself.

1.1. The current study

We proposed to examine these questions in the context of a spatial learning task that has proven highly sensitive to the cognitive effects of aging: the Groton Maze Learning Test (GMLT, Pietrzak et al., 2007; Snyder et al., 2005a,b; Thomas et al., 2008; Tippett et al., 2009). This computerized task assesses spatial learning across repeated trials as participants acquire and use an internal map to determine the location of a hidden maze path. The paths are learned through trial and error, with informative feedback provided after every move.

Exploratory and confirmatory factor analyses of GMLT responses have revealed two independent factors: error monitoring and maze-learning efficiency (Pietrzak et al., 2008). The error monitoring factor is thought to depend on the ability to inhibit inappropriate response tendencies, pay attention to feedback, and rapidly reorganize behavior "on-the-fly" while maintaining other information or functions. On the standard GMLT, this domain is measured by obtaining a total score for accuracy across GMLT trials (number of errors) as well as the number of perseverative errors and errors resulting from the breaking of simple task rules. In contrast, learning efficiency reflects visuomotor processing speed, visual attention, and short-term memory for spatial information, measured by how efficiently subjects complete the task (i.e., correct moves made per second). Thus, the GMLT was expected to capture age-related variance in both executive and nonexecutive aspects of maze performance that would then be examined in relation to central autonomic control (RSA), and peripheral cardiovascular activity (RPP).

Our version of the GMLT was modified from the original to assess performance across three levels of difficulty (easy, intermediate, difficult). Increasing the size and hence complexity of the maze paths was expected to increase attentional demands and increase the need for an efficient autonomic regulatory response. As well, we anticipated that older adults, relative to younger controls, would be more challenged by the demands of the maze learning task irrespective of grid size (Moffat et al., 2006; Newman and Kazniak, 2000). RSA, our measure of centrally modulated autonomic regulation, was calculated from the resting-state cardiac signal prior to the onset of the task. RPP, our measure of cardiac workload, was also calculated from resting heart rate and systolic blood pressure readings recorded during the baseline period. We expected that relatively greater autonomic disorganization would be associated with increased age (DeMeersman and Stein, 2007) and would be reflected in poorer maze performance, especially at higher levels of maze difficulty for those error-monitoring aspects of maze performance thought to reflect executive functions (Pietrzak et al., 2008).

2. Method

2.1. Participants

Twenty undergraduates (15 female; 18–26 years, $M = 20.4$), and twenty older adult volunteers (15 female; 65–87 years, $M = 74.6$) from the local community participated in the study. All had normal or corrected to normal vision, spoke fluent English, and were free from self-reported cardiac, neurological or psychiatric conditions, and from use of psychoactive medications.

Older adults scored within the normal range (27–30, $M = 28.6$, $SD = 1.08$) on the Mini-Mental Status Examination (Folstein et al., 1975). There was no difference in education levels between the two groups ($M_{Young} = 13.7$, $SD = 2.14$ years; $M_{Older} = 14.5$, $SD = 2.17$ years, $p > .20$) but, as expected, vocabulary level as measured by the SCOLP "Spot the Word" task (Baddeley et al., 1992) was higher for older adults ($M = 87\%$ correct), than for the younger group ($M = 79\%$ correct), $t(37) = 4.04$, $p < .001$. Reported symptoms of anxiety or depression on the Hospital Anxiety and Depression Scale (Zigmond and Snaith, 1983) for both younger ($M_{Anxiety} = 7.5 \pm 3.8$; $M_{Depression} = 1.7 \pm 1.7$) and older adults ($M_{Anxiety} = 4.70 \pm 3.0$; $M_{Depression} = 2.9 \pm 2.2$), were well below clinical levels (HADS: $M = 11$). The study received clearance from the Brock University Research Ethics Board and all participants provided written informed consent.

Although 20 older adults were originally enrolled in the study, three of them did not perform the maze task. Data from three more older adults were not used because they failed to complete the last level of the maze task and from one younger adult due to a technical problem, thus leaving data from 33 participants (19 younger; 14 older, 65–84, $M = 73.2$ years, 9 female) available for analysis.

2.2. Stimuli and experimental design

The GMLT (Pietrzak et al., 2007; Snyder et al., 2005b) was developed by one of us (P.J.S.), loosely based on a stepping stone design by Milner (1965). The task was further modified so that responses could be time-locked to ERPs recorded from individual participants. To increase spatial memory load and demands on attentional capacity, we included three difficulty levels: easy (4×4 grid), moderate (6×6 grid), and difficult (8×8 grid). At each level, the goal was to find a maze path that was hidden within a square grid of grey tiles. Beginning in the upper left corner and travelling toward the lower right corner, participants indicated which tile they thought might be next in the hidden path with a stylus on the touch-screen of a tablet laptop computer. Allowable choices were up, down, left, or right of the current tile. Diagonal moves were not allowed or recorded. After every step, the selected tile turned green for a correct choice or red for an incorrect one. When an incorrect tile was selected, participants were obliged to return to the previous correct tile and make a new selection. Performance of each maze was self-paced, but the timing of feedback was controlled in order to ensure that ERP responses to feedback were recorded although these are not reported here.

In the initial trials for each maze (learn trials), participants must depend on external feedback to learn the hidden path. However, on subsequent trials of the same maze (test trials), participants are able to make use of a developing internal map of the maze path in addition to receiving feedback. Behavioral accuracy was determined by recording the total number of steps required to complete a trial and calculating error scores off-line. Eight unique mazes were presented at the 4×4