Cardiac Autonomic Control During Simulated Driving With a Concurrent Verbal Working Memory Task

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Objective: The objective of the study was to illustrate sensitivity and diagnosticity differences between cardiac measures and lane-keeping measures of driving performance. **Background:** Previous research suggests that physiological measures can be sensitive to the effects of driving and side task performance and diagnostic of the source of the attentional demands. We hypothesized that increases in side task difficulty would elicit physiological change without reduction of driving task performance and that the side task demands would elicit patterns of autonomic activity that map to specific attentional processing resources. **Method:** Separately and concurrently, thirty-two participants performed a simulated driving task and verbal working memory task (with two levels of difficulty, 0 back and 3 back) separately and concurrently. Attentional demands were assessed through physiological and performance measures. **Results:** Cardiac measures reflected changes in attentional demand from single- to dual-task driving with an *n*-back task, whereas lane-keeping measures did not. Furthermore, patterns of autonomic activity elicited by driving, *n*-back task, and dual-task driving with a 3-back task were consistent with our predictions about autonomic activity. **Conclusion:** Changes in cardiac measures without changes in lane-keeping measures provide evidence that cardiac measures can be sensitive to hidden costs in attention that do not manifest in coarse measures of driving performance. Furthermore, correct predictions regarding the patterns of autonomic activity elicited suggests that cardiac measures can serve as diagnostic tools for attention assessment. **Application:** Because of the demonstrated differences in sensitivity and diagnosticity, researchers should consider the use of cardiac measures in addition to driving performance measures when studying attention in a driving simulator environment.

INTRODUCTION

With the introduction of new technologies into the automobile, driving is becoming an increasingly complex divided-attention task. The driver often engages in multiple tasks that require attention to multiple, simultaneously active input channels that sometimes require a response and may or may not be related to vehicular control or navigation. Research has shown that the addition of side tasks to the primary task of driving can have detrimental effects on driving performance.

In what some consider the first study to address driver workload, Brown, Tickner, and Simmonds (1969) demonstrated that adding a side task can have detrimental effects on the primary driving task (e.g., judgments of clearance). Since then, numerous studies have investigated the attentional effects of different side tasks or devices, such as navigation systems (e.g., Dingus, Hulse, & Barfield, 1998; Tsimhoni, Smith, & Green, 2004), cellular phones (e.g., Alm & Nilsson, 1994, 1995; Strayer, Drews, & Crouch, 2006), head-up displays (e.g., Wolffsohn, McBrien, Edgar, & Stout, 1998) speech interaction (e.g., Jamson, Westerman, Hockey, & Carsten, 2004; Lee, Caven, Haake, & Brown, 2001; Minker, Heisterkamp, & Scheible, 2004), and even music (e.g., Beh & Hirst, 1999) on driving performance.

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These studies showed that driving performance measures can be sensitive to the effects of divided attention while driving and that increases in attentional processes are required to perform dual or multiple tasks. However, other research has illustrated the occasional insensitivity of driving performance measures to changes in task demands during a complex driving task. Furthermore, there are many instances in which some driving performance measures reflect divided-attention demands whereas others do not. For example, although Brown et al. (1969) found that the addition of the side auditory task had a negative effect on the ability of the participant to judge gap clearances, it did not affect a number of other performance measures (e.g., lateral and longitudinal acceleration, the frequency of steering wheel and foot control use). In addition, some studies have demonstrated the occasional inability of performance measures to support hypotheses that the use of mobile telephones would lead to increases in lateral deviations (Alm & Nilsson, 1995; Parkes & Hooijmeijer, 2001).

Wickens's (1993) multiple resource theory of attention can explain why performance insensitivity may occur. He proposed that attentional resources available for task performance are limited and can be allocated strategically and that resource structure can be described by four different dichotomies: two stages of processing (perceptual-central and response), two modalities of perception (auditory and visual), two codes of processing (spatial and verbal), and, in Wickens (2002), two aspects of visual processing (focal and ambient).

Furthermore, it is important to note that Wickens's (1993) multiple resource theory does not rule out the possibility of a higher-order executive process to manage resources in a multiple task situation. According to Wickens, the resources within the four dichotomies are distinct, and it is competition for shared resources during a divided-attention task that will determine the degree of performance degradation from the single-task level. Performance should not be affected if the shared resources for multiple tasks are sufficient to meet task demands. But if one or more of the resources are not sufficient to meet desired performance on both tasks, or if one task is emphasized over the other, then performance on at least one of the tasks should decline.

Therefore, the absence of a performance decrement does not mean that there are no attention costs attributable to dual-task performance. It may mean that resources were not shared between tasks, but it could also mean that shared resources were not overtaxed. An in-vehicle technology (IVT) that does not induce driving performance decrements when it is used while driving is emblematic of good design. We contend that reliance solely on performance measures to evaluate the effect of an IVT on driving is problematic because performance measures cannot distinguish between these two alternative explanations for the absence of performance decrements, which have very different implications for driving safety. An IVT design that minimizes shared resources with driving (e.g., auditory modality, verbal coding, and vocal input) should be superior to an IVT design that shares resources with driving (e.g., visual modality, spatial coding, and manual input) in situations where more resources need to be devoted to driving because of environmental challenges (such as increased traffic density or poor weather) or hazard avoidance (Recarte & Nunes, 2000; however, engaging conversations on mobile telephones may be an exception; cf. Recarte & Nunes, 2003).

Thus, other measures may be needed in addition to performance to better assess the attentional costs of IVTs. To overcome performance insensitivity, Backs (1995) and many others suggest the use of physiological measures. Physiological measures can be more sensitive than performance or subjective measures because they may change before other measures, and changes in physiological measures may occur without changes in other measures (Kramer, 1991).

The use of physiological measures can sometimes compensate for performance insensitivity; changes in task demands may not be reflected by changes in performance (e.g., driving) but may be reflected by changes in physiological measures (e.g., heart rate, heart rate variability). In fact, research has illustrated that change in cardiac measures can occur without changes in driving performance measures as the driver divides his or her attention or as the demands of the driving task increase. For example, Lenneman, Shelley, and Backs (2005) were able to show that dual-task driving and a verbal working memory task elicited changes in heart rate, whereas there was no change in the maintenance of lateral control during simulated driving. Furthermore, Brookhuis, De Vries, and De Waard (1991) were able to show that dual-task on-road driving and a verbal serial addition task presented via cell phone elicited significant increases in heart rate and decreases in heart rate variability, whereas the maintenance of lateral control of the vehicle actually improved over that in driving-only conditions.

Backs (1995, 2001) has suggested that the advent of autonomic space theory has increased both the sensitivity and diagnosticity of cardiac measures of attention. Sensitivity is increased because changes in task demands can be detected in autonomic space that may not be detected in end-organ measures, such as heart rate. Diagnosticity is increased because the control modes for heart rate are thought to map to the processing-stage attentional resources defined by Wickens's (1993, 2002) multiple resource theory.

The Doctrine of Autonomic Space

The heart is dually innervated by the sympathetic and parasympathetic branches of the autonomic nervous system (ANS). Sympathetic activation causes an increase in heart rate, whereas parasympathetic activation causes a decrease in heart rate. In the classic model of ANS function, activity of these branches was thought to be reciprocal: Change in heart rate was the result of activation of one branch coupled with withdrawal of the other branch (Cannon, 1932). The "doctrine of autonomic space" posits that ANS activity is multidimensionally determined instead of only reciprocally coupled (Berntson, Cacioppo, & Quigley, 1991; Berntson, Cacioppo, Quigley, & Fabro, 1994). In addition to the reciprocally coupled modes, the sympathetic and parasympathetic branches can be nonreciprocally coupled (coactivation or coinhibition) or even uncoupled (change in activity of one branch is not coupled with a change in activity of the other branch). Thus, instead of a change in heart rate being caused by a change in activation of one branch and withdrawal of the other, eight modes of autonomic control exist (see Figure 1).

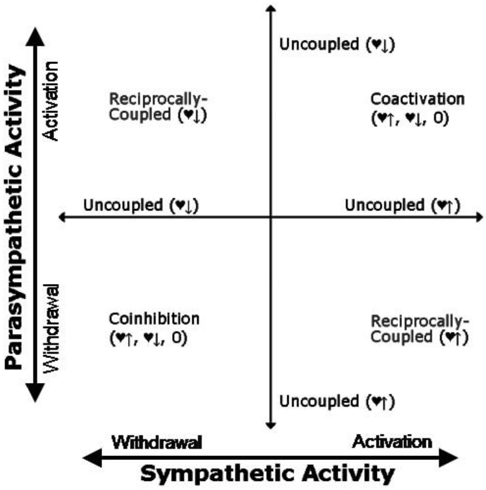

Figure 1. The eight modes of autonomic control. Traditional coupled modes in italics; ♥ = heart rate. Coinhibition and coactivation have multiple responses for heart rate depending on the amount of activation or inhibition of the two autonomic branches.

To determine the mode of autonomic control responsible for the observed heart rate, noninvasive measures of underlying sympathetic and parasympathetic neural activity are needed. Previous research using pharmacological blockades have shown that preejection period (PEP) and respiratory sinus arrhythmia (RSA) can serve as valid measures of sympathetic and parasympathetic activity, respectively (Cacioppo et al., 1994; Stemmler, 1993). Increases in PEP reflect decreases in sympathetic activity, whereas decreases in PEP reflect increases in sympathetic activity. In contrast, increases in RSA reflect increases in parasympathetic activity, whereas decreases in RSA reflect decreases in parasympathetic activity. In the current study, PEP and RSA were the measures used to assess the modes of autonomic control for the heart.

A physiological measure is diagnostic to the extent that it indexes specific psychological processes, that is, the extent to which the measure exhibits a one-to-one psychological-physiological mapping (Cacioppo & Tassinary, 1990). Previous research has shown that central processing tasks (e.g., mental arithmetic) elicit reciprocally coupled sympathetic activation and parasympathetic withdrawal (Berntson, Cacioppo, & Fieldstone, 1996; Wetzel, Quigley, Morell, Eves, & Backs, 2006). Tasks that require primarily perceptual-motor processing (e.g., manual tracking) elicit uncoupled parasympathetic withdrawal (Backs, Rhody, & Barnard, 2005; Lenneman & Backs, 2000). In addition, Backs et al. (2005) found that adding monitoring tasks that required perceptual-central and motor processing to a tracking task that required perceptual-motor processing (thus creating competition primarily for motor resources) increased parasympathetic withdrawal but had no effect on sympathetic activity. Finally, executive attentional processes (for higher-order strategies during dual-task performance) are thought to elicit uncoupled sympathetic activation (Backs, 1998). Recent research has confirmed that some of these modes of autonomic control are elicited during simulated driving as well (Backs, Lenneman, Wetzel, & Green, 2003; Lenneman et al., 2005).

Purpose of the Study

The purpose of the present study was twofold. The first purpose was to illustrate the sensitivity differences between cardiac measures and lane-keeping measures of simulated driving performance. On the basis of previous findings (i.e., Brookhuis et al., 1991; Lenneman et al., 2005), we proposed that we would see differences between cardiac measures and lane-keeping measures of driving performance in detecting changes in attentional demands (a) from single- to dual-task performance and (b) as the attentional demands increase from low to high levels of task difficulty during single- and dual-task performance.

In the current study, participants were required to perform two tasks, sometimes concurrently: a simulated driving task along a straight road with varying crosswinds and a verbal working memory *n*-back side task. During an *n*-back task, the participant was required to decide whether the currently presented letter matched the *n*th letter previously presented (the target stimulus) in a series of sequentially presented letters. Previous research has shown that as *n* increases, the amount of working memory processing resources required to perform the task increases, resulting in slower reaction time (RT) and lower accuracy (McElree, 2001; Smith & Jonides, 1997).

The second purpose of the study was to test the utility of the autonomic space model for deciphering psychological-physiological mappings. We predicted that heart rate would increase as the attention demands of the *n*-back task increased (e.g., Hansen, Johnson, & Thayer, 2003). However, the pattern of autonomic activity (i.e., the mode of autonomic control) responsible for a heart rate increase would differ depending on which attentional resources in Wickens's (1993, 2002) model are being loaded by increases in task difficulty (going from 0-back task to 3-back task) or by competition between tasks (going from driving alone to driving with the side task). Confirmation of our hypotheses would reaffirm the utility of the autonomic space model as a method for deciphering psychological-physiological mappings during simulated driving (e.g., Backs et al., 2003).

First, we predicted that the driving-only task would elicit an increase in heart rate over resting baseline attributable to a decrease in RSA with no change in PEP (i.e., uncoupled parasympathetic withdrawal mode of autonomic control) because it primarily demands visual perceptual-motor response processing resources. Second, we predicted that the *n*-back task would elicit an increase in heart rate over resting baseline attributable to a decrease in RSA and a shortening of PEP (reciprocally coupled sympathetic activation and parasympathetic withdrawal mode of autonomic control) because it primarily demands visual perceptual-central processing resources with minimal motor response processing resources. Furthermore, we predicted that the magnitude of the increase in heart rate and the change in reciprocally coupled sympathetic activation and parasympathetic withdrawal would be greater as the amount of central processing resources needed to perform the *n*-back task increases from 0 back to 3 back in both the single- and dual-task conditions.

Finally, we predicted that adding the *n*-back task to driving would also elicit an increase in heart rate attributable to a decrease in RSA and a shortening of PEP that should increase with *n*-back difficulty. Resource competition between tasks will occur when adding the visual perceptual-central and motor processing of the *n*-back task to the visual perceptual-motor processing of simulated driving (and executive processing demands may also be elicited for task coordination), which will result in a reciprocally coupled sympathetic activation and parasympathetic withdrawal mode of autonomic control that increases from driving only to driving with the 0-back side task to driving with the 3-back side task.

METHOD

Participants

For the study, 32 participants (16 male, 16 female), who were in good health and were not taking any medications that affect the cardiovascular system, were recruited through the Department of Psychology subject pool to participate. Participants ranged in age from 18 to 34 (mean = 19.8) years. The number of miles driven per year for the participants ranged from 2,000 to 35,000 miles (mean = 8,700 miles).

Apparatus

The electro- and impedance cardiograms were obtained from an impedance cardiograph using a Pentium computer running Mindware Acquisition (Version 2.0; Mindware Technologies) data acquisition system. Impedance cardiogram data for 2 participants were collected using a Minnesota Impedance Cardiograph Model 304b, and data for the other 30 participants were collected using a Mindware Impedance Cardiograph Model 2000. One spot electrode was placed approximately 5 cm to the left of the suprasternal notch on each participant's sternum with two electrodes placed over the fifth intercostal space on the participant's left and right thorax for electrocardiogram (ECG). For impedance cardiography, two voltage electrodes were placed below the suprasternal notch and the xiphoid process, and two current electrodes were placed on the back approximately 3 to 4 cm above and below the voltage electrodes, respectively. A desktop DriveSafety driving simulator running HyperDrive software (Version 1.9.25) was used to present the driving task, and a second computer connected to the simulator presented the concurrent *n*-back task.

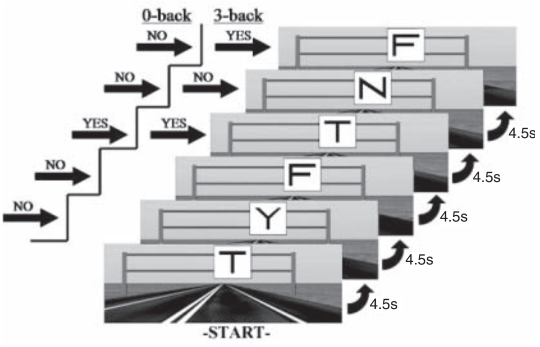

Figure 2. A 0-back and 3-back task presented on road signs in the simulated environment.

Procedure

The participants performed two tasks during the study. The first was a simulated driving task in which the participants had to steer while the velocity was controlled by the computer. The participants were instructed to maintain their position in the lane as best as possible (drive a straight line). The driving environment depicted in the simulation was a straight, two-lane road with no traffic ahead (see Figure 2). Wind disturbance during each trial was simulated by applying a random amount of force between 0 and 1,000 N perpendicular to the direction of the car from either the left or the right every 10 s. Tactile feedback (steering wheel vibration) was given to the driver if the vehicle exceeded the left or right edge line.

The second task was a verbal working memory *n*-back task presented at one of two levels of difficulty: 0 back and 3 back. During the 0-back task, the participant was required to specify whether the current letter was the same as the first letter presented at the beginning of the simulation run (the target). During the 3-back task, the participant was required to specify whether the current letter matched the letter that was presented three letters previously (the target; see Figure 2). During both *n*-back tasks, the participants signaled whether the letter and target matched by pressing different buttons on the steering wheel.

The letters for the *n*-back task (angular consonants) were presented on road signs placed every 90 m. Thus, when traveling at 72.4 km/h (45 mph), the letters were presented to the driver every 4.5 s. During each repetition of the *n*-back task, a total of 53 letters were presented to the participant, of which 15 matched the target (30%). When the *n*-back task was performed alone (single-task conditions), the driving simulation was still presented but with steering, braking, and acceleration all controlled by computer.

At the beginning of the session, participants practiced a driving-only condition once, in which the driving environment in the driving-only condition was the same as in the *n*-back conditions except that no letters were presented on the road signs. After the driving-only condition, participants practiced at least one trial of each of the four *n*-back conditions (single task, 0 back; driving with the 0-back side task; single task, 3 back; and driving with the 3-back side task). The practice *n*-back conditions were repeated until participants could perform under each condition with at least 75% accuracy. Participants were instructed to perform their best on both tasks in the dual-task conditions.

Following practice, participants were given a 10-min break, during which electrodes were applied. Following application of the electrodes, an 8-min resting baseline was collected, followed by the experimental trials. The first experimental trial was a driving-only condition. The driving-only trial was followed by 12 *n*-back trials, during which the four *n*-back conditions were presented in an order specified by a Latin square, with the order repeated three times. After the 12 *n*-back trials, participants completed a second driving-only condition, which was followed by a second 8-min resting baseline.

Data Quantification

Electro- and impedance cardiography were used to obtain noninvasive indices of sympathetic and parasympathetic nervous system activity (Berntson et al., 1997). We used heart period as the end organ measure of cardiac activity rather than heart rate because of its superior biometric properties (Berntson, Cacioppo, & Quigley, 1995). Heart period was calculated as the time in milliseconds between successive R-peaks (or spikes) of the ECG, so that an increase in heart rate results in shortening of heart period. RSA (the parasympathetic index) was calculated as the natural logarithm of the power in the high-frequency heart period variability frequency band (0.12 to 0.40 Hz) by applying fast Fourier transform (FFT) to the resampled R-R intervals (or time between consecutive R-peaks) using Mindware HRV (Version 2.2; Mindware Technologies). PEP (the sympathetic index), which is the time between the onset of ventricular depolarization and the onset of left ventricular ejection into the aorta, was obtained from the first derivative of pulsatile changes in transthoracic impedance (dZ/dt) using Mindware IMP (Version 2.2; Mindware Technologies). Respiration data was collected as a control measure to aid in the interpretation of RSA. Respiration rate in breaths per minute was obtained from the dZ/dt data (Ernst, Litvack, Lozano, Cacioppo, & Berntson, 1999). Respiration amplitude was obtained in arbitrary units from an FFT of the resampled respiration data.

Performance measures were collected for both the simulated driving task and the *n*-back task. Performance on the driving task was measured as the root mean squared of lateral deviation (RMSld) between the center of vehicle and the lane center (in meters) and as the standard deviation of steering wheel angle (SDsw; in radians) collected at a rate of 60 Hz. Performance on the *n*-back task was measured as RT in milliseconds from the stimulus presentation to the participant's key press and as the proportion correct responses in each trial.

All data were collected for the entire 243 s of the experimental trials, of which the first 18 s were used to accelerate the vehicle to cruising speed. Physiological data were analyzed for the remaining 225 s in two segments of 112.5 s each. Performance data were analyzed in a single 225-s segment. Physiological data were also analyzed for the final 225 s of the resting baselines in two segments of 112.5 s each. A mean resting baseline for each measure

TABLE 1: Means and Standard Deviations for Physiological Difference Scores for Single-Task Driving-Only and Single-Task *N*-Back Conditions

	Single Task, Driving Only		Single Task, *N* Back	
Measure	*M*	*SD*	*M*	*SD*
Cardiac				
Heart period (milliseconds)	3.74	6.47	–27.09***	6.48
Preejection period (milliseconds)	–1.80	1.10	–2.40*	1.10
Respiratory sinus arrhythmia $[\ln(\text{ms})^2]$	–0.26***	0.07	–0.19*	0.08
Respiration				
Rate (breaths/minute)	1.16*	0.44	0.72	0.62
Amplitude (arbitrary units)	–0.0001	0.004	–0.004	0.003

Significant change from baseline: $^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

was calculated as the mean across the two resting baseline trials. Difference scores for each trial were calculated as the change between the raw score of a measure and the mean resting baseline score for that measure. Positive scores indicate an increase in the measure from baseline to task, whereas negative scores indicate a decrease in the measure from baseline to task. Only 17 samples of physiological data from a total of 3,200 samples (0.53%) were missing. The values of the missing data were estimated by regression across the nonmissing data for the relevant task and participant.

RESULTS

The hypotheses in the present study concern the effects of adding the *n*-back side task to driving. Therefore, all analyses used the first and third repetitions of each *n*-back condition because there were only two driving-only conditions (one before and one after the 12 *n*-back trials). The effects of adding driving to the *n*-back task were examined in a separate article (Lenneman & Backs, 2007) and are contrasted with the effects of adding the *n*-back task to driving in the Discussion. SPSS for Windows Version 13.0 (Green, Salkind, & Akey, 2000) was used for all analyses. An alpha of .05 was used to determine statistical significance, and we used the Huynh-Feldt epsilon corrected probability level for repeated-measures factors with more than two levels.

Single Tasks

To test our predictions regarding the effects of single-task driving-only and single-task *n*-back performance on the change in autonomic space from resting baseline for each task, *t* tests were done for heart period, PEP, RSA, respiration rate, and respiration amplitude difference scores collapsed across trial and segment. The driving-only condition elicited a significant decrease in RSA, $t(31) = -13.25$, $p < .001$, and increase in respiration rate, $t(31) = 6.81$, $p < .05$, but there was no significant change in heart period, PEP, or respiration amplitude (see Table 1). Although heart period did not change, we found an uncoupled parasympathetic withdrawal mode of control that was consistent with our prediction for the driving-only single task.

RSA is thought to primarily reflect vagus nerve input at the sinoatrial node of the heart, and it is negatively correlated with respiration rate (Berntson et al., 1997). The increase in respiration rate from resting baseline was significant for the driving-only condition; however, we do not believe that the significant decrease in RSA in this condition was attributable solely to respiratory change for several reasons. First, the correlation between RSA and respiration rate was similar for the driving-only ($r = -.57$, $p < .001$) and *n*-back ($r = -.54$, $p < .001$) task condition, where there was no significant change in respiration rate from resting baseline. Furthermore, these within-task correlations are similar to

TABLE 2: Means and Standard Deviations for Physiological Difference Scores for Single-Task 0-Back and Single-Task 3-Back Conditions

	Single Task, 0 Back		Single Task, 3 Back	
Measure	*M*	*SD*	*M*	*SD*
Cardiac				
Heart period (milliseconds)***	–6.89	5.50	–47.29	9.26
Preejection period (milliseconds)	–1.77	0.93	–3.04	1.69
Respiratory sinus arrhythmia [ln(ms)^2]**	–0.03	0.07	–0.36	0.11
Respiration				
Rate (breaths/minute)	0.84	0.66	0.60	0.66
Amplitude (arbitrary units)	–0.001	0.004	–0.01	0.004
Performance				
Reaction time (seconds)***	0.63	0.03	0.86	0.05
Accuracy (proportion correct)**	0.97	0.02	0.89	0.02

Significant change from 0-back to 3-back task condition: *$p < .05$. **$p < .01$. ***$p < .001$.

between-task correlations between RSA and respiration rate ($r = -.55$, $p < .001$, for driving-only RSA with *n*-back respiration rate; and $r = -.50$, $p < .001$ for driving-only respiration rate with *n*-back RSA). Finally, the within-task correlations are smaller than the between-task reliabilities for both RSA ($r = .71$, $p < .001$) and respiration rate ($r = .85$, $p < .001$).

The *n*-back task, collapsed across 0-back and 3-back tasks, elicited a significant decrease in heart period, $t(31) = -17.46$, $p < .001$; PEP, $t(31) = -4.75$, $p < .05$; and RSA, $t(31) = -6.48$, $p < .05$; but there was no significant change in respiration rate or amplitude. Consistent with our prediction for the *n*-back task, we found a heart period decrease (increase in heart rate) that was attributable to reciprocally coupled sympathetic activation and parasympathetic withdrawal mode of autonomic control.

Furthermore, to test our prediction regarding the change in attentional resources needed to perform the 3-back task compared with the 0-back task, a 2 (task: 0 back, 3 back) × 2 (trial) × 2 (segment) repeated-measures ANOVA was performed for heart period, PEP, RSA, respiration rate, and respiration amplitude (see Table 2). The main effect of task was significant for heart period, $F(1, 31) = 25.55$, $p < .001$, and RSA, $F(1, 31) = 9.73$, $p < .01$, but not for PEP, respiration rate, and respiration amplitude (see Table 2). Heart period and RSA significantly decreased from the 0-back task to the 3-back task. Finally, a 2 (task: 0 back, 3 back) × 2 (trial) repeated-measures ANOVA was performed for *n*-back RT and accuracy. The main effect of task was significant for RT, $F(1, 31) = 46.90$, $p < .001$, and accuracy, $F(1, 31) = 7.97$, $p < .01$. Reaction time increased and accuracy decreased from the 0-back to the 3-back task.

In, summary, the single-task results generally support our hypotheses regarding the pattern of autonomic activity that each task would elicit. The driving-only task did elicit uncoupled parasympathetic withdrawal, and the *n*-back task (collapsed across both levels of difficulty) did elicit reciprocally coupled sympathetic activation and parasympathetic withdrawal. However, we had predicted that the increase in attentional resources needed to perform the 3-back compared with the 0-back task would elicit an increase in the magnitude of reciprocally coupled sympathetic activation and parasympathetic withdrawal. Parasympathetic withdrawal significantly increased as workload increased from 0-back to 3-back difficulty, but the increase in sympathetic activation only approached significance.

Dual Tasks

Performance. Prior to testing the effects of adding the *n*-back side task to driving, we conducted a manipulation check to determine

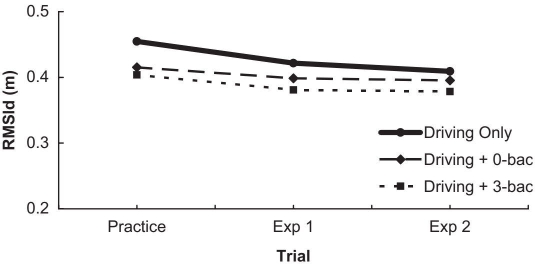

Figure 3. Root mean squared of lateral deviation for the first practice trial for each condition and the two trials used in the single-to-dual task analysis in Table 3. $n = 30$.

whether the driving task was resource limited, that is, to see if performance improved with practice. We were able to retrieve practice data for RMSld from 30 participants. The practice trials were presented in a fixed order beginning with driving only, and although a few participants required more than one practice trial to reach the *n*-back performance criterion for the dual tasks, only the first practice trial was used for the 3 (task: driving only, driving with 0-back task, driving with 3-back task) × 3 (trial) repeated-measures ANOVA that was conducted for RMSld.

As shown in Figure 3, driving performance did improve from practice to the experimental trials, $F(2, 58) = 5.58$, $p < .013$, epsilon = .72. Driving performance in the practice trial was significantly worse than in the two experimental trials, which did not differ from each other according to post hoc Helmert contrasts, indicating that the driving task was resource limited. The main effect of task was also significant in this analysis, $F(2, 58) = 7.03$, $p < .004$, epsilon = .81, where driving only had significantly worse performance than the two dual tasks, which did not differ from each other according to post hoc Helmert contrasts. However, this main effect was observed because the driving-only practice trial came first: A contrast between the driving only practice trial and the dual-task practice trials was significant, $F(1, 58) = 4.23$, $p < .05$, but a comparison between the two dual-task practice trials was not.

A 3 (task: driving only, driving with 0-back task, driving with 3-back task) × 2 (trial) repeated-measures ANOVA was conducted for RMSld and SDsw to test the effects of adding the *n*-back task to driving on driving performance in the experimental trials. The effects of task or trial were not significant for RMSld or SDsw. Driving performance did not change significantly from single-task driving only to dual-task driving with the 0-back or the 3-back side task (see Table 3).

A 2 (task: driving with 0-back task, driving with 3-back task) × 2 (trial) repeated-measures ANOVA was conducted for RT and accuracy to test the effects of memory load on dual-task performance of the *n*-back task. The main effect of task was significant for RT, $F(1, 31) = 86.71$, $p < .001$, and accuracy, $F(1, 31) = 33.61$, $p < .001$. RT increased and accuracy decreased as difficulty increased from driving with the 0-back task to driving with the 3-back task (see Table 3). The main effect of trial was significant for RT, $F(1, 31) = 4.37$, $p < .05$, but not for accuracy. RT decreased from the first to last *n*-back trial (whereas accuracy remained unchanged), but *t* tests show that the performance improvement was significant only for the 3-back task, $t(31) = -4.45$, $p < .05$.

Physiological. To test our predictions regarding the effects of adding the *n*-back task to driving on the physiological measures, a 3 (task: driving only, driving with 0-back task, driving with 3-back task) × 2 (trial) × 2 (segment) repeated-measures ANOVA was conducted for heart period, PEP, RSA, respiration rate, and respiration amplitude (see Table 3). Post hoc tests were conducted between single-task driving-only and dual-task driving conditions and between both dual-task driving conditions for each measure that had a significant task effect.

The main effect of task was significant for heart period, $F(2, 62) = 59.19$, $p < .001$, epsilon = .95; PEP, $F(2, 62) = 4.74$, $p < .05$, epsilon = .91; and RSA, $F(2, 62) = 6.71$, $p < .01$, epsilon = .96. Heart period, PEP, and RSA decreased significantly from single-task driving only to dual-task driving with *n*-back task (see Table 3). Single- to dual-task change for heart period was significant for driving with 0-back task, $F(1, 31) = 23.25$, $p < .001$, and for driving with 3-back task, $F(1, 31) = 89.77$, $p < .001$. Heart period change from driving with 0-back task to driving with 3-back task was also

TABLE 3: Means and Standard Deviations for Physiological Difference Scores and Performance for Single-Task Driving-Only Condition and Both Dual-Task Driving Conditions With *N*-Back Task

	Single Task, Driving Only		Dual Task, Driving With 0-Back Task		Dual Task, Driving With 3-Back Task	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*
Cardiac						
Heart period (milliseconds)***	3.74	6.47	–19.00	6.42	–56.24	8.18
Preejection period (milliseconds)*	–1.80	1.10	–2.40	1.24	–3.85	1.36
Respiratory sinus arrhythmia [ln(ms)^2]*	–0.26	0.07	–0.25	0.08	–0.51	0.10
Respiration						
Rate (breaths/minute)*	1.16	0.44	0.99	0.59	–0.05	0.61
Amplitude (arbitrary units)	–.0001	0.004	–0.004	0.004	–0.005	0.004
Performance						
RMSld (meters)	0.41	0.02	0.40	0.02	0.38	0.02
SDsw (radians)	4.43	0.38	4.21	0.24	4.02	0.22
Reaction time (seconds)***	N/A		0.59	0.03	0.86	0.04
Accuracy (proportion correct)***	N/A		0.99	0.01	0.89	0.02

Note. RMSld = root mean squared of lateral deviation; SDsw = standard deviation of steering wheel angle. Significant task effect: *$p < .05$. **$p < .01$. ***$p < .001$. See text for post hoc tests.

significant, $F(1, 31) = 45.27$, $p < .001$. The single- to dual-task decrease for PEP was significant for driving with the 3-back task, $F(1, 31) = 6.89$, $p < .05$, but not for driving with the 0-back task; however, the PEP decrease from driving with the 0-back task to driving with the 3-back task was significant, $F(1, 31) = 7.16$, $p < .05$. Like PEP, the single- to dual-task decrease for RSA was significant for driving with the 3-back task, $F(1, 31) = 9.69$, $p < .01$, but not for driving with the 0-back task, and the RSA decrease from driving with the 0-back task to driving with the 3-back task was significant, $F(1, 31) = 8.24$, $p < .01$.

These results show a significant change in autonomic space from single-task driving-only to dual-task driving and *n*-back performance. Although heart period was significantly shorter (faster heart rate) across all three tasks, the change in autonomic space was primarily caused by the increased attentional resource demands required to perform the 3-back dual task. No significant change in autonomic space was elicited by dual-task driving with 0-back performance compared to driving only, whereas dual-task driving with 3-back performance elicited greater reciprocally coupled sympathetic activation and parasympathetic withdrawal compared with driving only and dual-task driving with 0-back performance (see Figure 4). So unlike in the single task, reciprocally coupled change with *n*-back task difficulty was significant for the dual tasks.

The main effect of trial was significant for heart period, $F(1, 31) = 26.64$, $p < .001$, and RSA, $F(1, 31) = 9.70$, $p < .01$, but not for PEP. The main effect of segment, $F(1, 31) = 20.55$, $p < .001$, and the interaction between task and trial, $F(1, 31) = 5.20$, $p < .01$, were significant only for heart period. Heart period lengthened (heart rate decreased) from the first to last trials of the session, and RSA increased from the first to the last trial of the session. These results indicate that parasympathetic activity increased from the first to last trials of the session; however, the decrease compared with baseline was still significant for the last trial.

The main effect of task was significant for respiration rate, $F(2, 62) = 5.73$, $p < .01$, epsilon = .98, but not for respiration amplitude. Respiration rate decreased significantly from single-task driving only to the *n*-back task (see Table 3). Single- to dual-task change for respiration rate was significant for driving with the 3-back task, $F(1, 31) = 8.28$, $p < .01$, and from driving with the 0-back task to driving with the

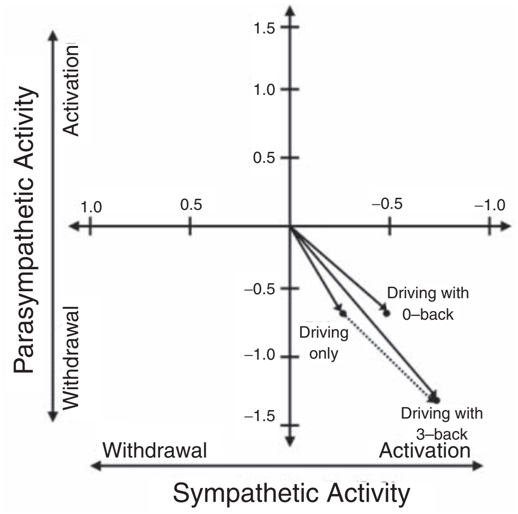

Figure 4. Standardized preejection period (PEP; *x*-axis) and respiratory sinus arrhythmia (RSA; *y*-axis) difference scores representing sympathetic and parasympathetic change from resting baseline (the origin). Standardized scores were computed by dividing the mean difference score by the standard deviation for PEP and RSA across all the tasks. Change from the origin along the negative diagonal indicates a reciprocally coupled mode of control (sympathetic activation and parasympathetic withdrawal). Change from the origin along the *x*-axis indicates an uncoupled sympathetic mode of control, and change along the *y*-axis indicates an uncoupled parasympathetic mode of control. Solid vectors from the origin represent the change in autonomic space from resting baseline for each of the tasks. Dashed vectors from one task to another represent a significant change in autonomic space between tasks. The autonomic mode of control for single-task driving only is uncoupled parasympathetic withdrawal. The vector from single-task driving only to dual-task driving with 3-back task represents the elicitation of reciprocally coupled sympathetic activation and parasympathetic withdrawal after adding the 3-back task to driving.

3-back task, $F(1, 31) = 6.50$, $p < .05$. However, these rate changes were in the opposite direction of the RSA change, so they do not affect the conclusions drawn earlier about autonomic space.

DISCUSSION

Previous research has shown that cardiac measures can be more sensitive to changes in attentional demands than driving performance measures (Brookhuis et al., 1991; Lenneman et al., 2005). The current study underscores that notion. Lane keeping did not reflect assumed increases in attentional demand from single-task driving to dual-task driving with an *n*-back task, whereas cardiac measures did. Heart period and autonomic space both reflected the increase in attentional demand across task difficulty.

The use of cardiac measures can enable researchers to gain insights into the hidden attentional demands of a task that may not be detected by traditional performance measures. For example, in the current study, we believe that dual-task driving with an *n*-back task does impose additional attentional demands when compared to single-task driving only, particularly during dual-task driving with the 3-back task, because of resource competition for visual, central, and motor processing resources. However, the attentional demands imposed were not great enough to manifest themselves as decrements in lane keeping (or steering wheel angle). Without the cardiac data, one might incorrectly conclude that neither the 0-back nor the 3-back task had significant resource competition with driving. Instead, the cardiac data indicate that participants needed to increase their effort in response to the demands of the dual tasks but still had enough residual processing resource capacity to prevent driving performance decrements.

In the current study, we found that increases in attentional demand across tasks were apparent in measures of cardiac activity through a decrease in heart period (faster heart rate) and significant change in the pattern of autonomic activity with respect to the autonomic space model (Backs, 1995, 2001). Although the purpose of this study was to see whether cardiac measures were more sensitive than driving performance when adding to driving a visual perceptual-central task that required verbal processing and a manual response (which could encompass the processing demands of many existing and proposed IVTs), we also examined the cardiac and *n*-back performance measures when adding driving to the *n*-back task (reported in Lenneman & Backs, 2007). Like the current study, in the previous study, we found that the cardiac measures and autonomic space were significantly more sensitive and diagnostic to processing resource competition during dual-task performance than were the *n*-back performance measures, which either did not differ or improved from single-task to dual-task *n*-back conditions (cf. Tables 2 and 3 in the current study).

An increase in effort in the face of dual-task resource competition could offset driving performance decrements, as well as *n*-back performance decrements, from the single to the dual tasks (Brookhuis et al., 1991). The absence of performance decrements when dividing attention is certainly indicative that simulated driving and the *n*-back task could be time shared perfectly (when visual scanning is minimized as it was in the current study and would be for an IVT that used a head-up display). However, the greater sensitivity of the cardiac measures serve to remind a designer that perfect time sharing is not free of attention costs, even when there is minimal resource competition.

It has also been suggested that measures of autonomic space are more diagnostic of the source of attentional demands (e.g., Backs, 1995, 2001) than are performance measures. On the basis of the results of previous studies that established a pattern of autonomic activity elicited by specific psychological processes during manual tracking, we predicted a mode of autonomic control of the heart that would be elicited by the simulated driving and *n*-back tasks in both single- and dual-task settings. We correctly predicted that simulated driving would elicit an uncoupled parasympathetic withdrawal mode of autonomic control and that a single-task *n*-back condition would elicit reciprocally coupled sympathetic activation and parasympathetic withdrawal mode of control in autonomic space.

These results are consistent with previous research that suggests autonomic space can be used to differentiate perceptual-motor processes from perceptual-central processes in single-task environments (e.g., Backs et al., 2005; Berntson et al., 1996; Lenneman & Backs, 2000; Wetzel et al., 2006). However, our prediction that the change in difficulty in a single-task *n*-back setting would elicit an increase in reciprocally coupled sympathetic activation and parasympathetic withdrawal was not fully supported (although the change in autonomic activity was in the predicted direction). In contrast, for dual-task performance, we correctly predicted that adding the *n*-back task to simulated driving would elicit a decrease in RSA and a shortening of PEP, indicative of a reciprocally sympathetic activation and parasympathetic withdrawal.

Thus, to this point, we have demonstrated that cardiac measures of attentional demands can be more sensitive to changes in attentional demands and more diagnostic to the source of the attentional demands during task performance than lane-keeping measures of simulated driving performance or RT and accuracy measures of side-task performance. The failure to elicit a shortening of PEP (greater sympathetic activation) during dual-task driving with a 0-back task seems to indicate that the autonomic mode of control may not be a good indicator of the use of central processes in dual-task performance in low workload situations. However, we offer several alternative reasons why the predicted mode of autonomic control was not found.

First, we believe that the failure to elicit sympathetic activation during dual-task driving with a 0-back task in the current study could be attributable to the relative lack of executive processing demands during dual-task driving with the 0-back side task. Support for this contention is provided by the work of Smith and Jonides (1997), who reported a series of positron emission tomography studies in which they found that performance of the 2- and 3-back tasks (but not the 0-back or 1-back tasks, which are essentially item-recognition tasks) elicited recruitment of the dorsolateral prefrontal cortex, which has previously been shown to mediate executive processes during *n*-back performance.

It has also been suggested that the activity of maintaining a vehicle in the center of the lane (e.g., the simulated driving task used in the current study) requires the use of ambient vision and that processing ambient visual information may be preattentive or automated (Horrey, Wickens, & Consalus, 2006; Wickens, 2002). If so, concurrent performance of the simulated driving task and the 0-back task would not generate sufficient visual attentional resource competition between the two tasks to necessitate the use of extensive executive processing during task performance.

Finally, the failure to elicit sympathetic activation during dual-task driving with the 0-back task in the current study could be attributable to an increase in processing efficiency. Electroencephalographic studies during complex and working memory tasks have shown that cortical activation decreases with increased practice (e.g., Gevins, Smith, McEvoy, & Yu, 1997; Kramer & Strayer, 1988). In turn, as people become more efficient, fewer executive processes may be necessary to perform the task later as opposed to earlier in practice. Although Backs (1998) showed that the use of executive processes for dual-task performance elicits significant sympathetic activity, Backs et al. (2005) found that sympathetic activation wanes over time as the number of executive processes used for task performance presumably decreases.

We believe that an increase in efficiency of executive processes may have begun during the practice session and continued through the testing session. The finding that RT significantly decreased across trials for dual-task driving with the 3-back task but had already stabilized for dual-task driving with the 0-back task supports the notion that by the time the testing session began, sympathetic activity in the 0-back dual task could have already begun to wane, resulting in nonsignificant PEP change. However, it is a limitation of the current study that physiological data were not collected during practice, and future studies should examine more closely the time course of different response systems.

Some other limitations of the study should also be noted. Although we have suggested that the *n*-back task imposes visual perceptual-central and motor processing demands, the *n*-back task we used may have had minimal demands on visual (because of the lack of separation between *n*-back stimuli location and the driving scene) or motor (because the timing of the *n*-back stimulus presentation and the wind disturbances were not related) processing resources. Thus, attention resource demand of dual-task driving and *n*-back performance in this study may have been only in terms of central processing and not among the dichotomies in Wickens's (2002) multiple resource theory (Recartes & Nunes, 2000). However, both of these limitations could be addressed in future studies by including a side task that requires more difficult visual-perceptual or spatial discrimination and by better controlling both the temporal presentation of the side-task stimuli and the driving difficulty manipulations.

Summary and Applications

Sensitivity differences among measures should be considered when choosing measures of attention in future simulated driving research studies. Specifically, cardiac measures can provide the researcher with information about potential hidden costs to attention of side-task performance that may not be reflected in performance measures. Thus, physiological measures could be used to choose between two designs that may not be considered detrimental to driving performance but may have differing effects on cognitive demand (and perhaps to driving safety) as shown by physiological measures. Although the current study analyzed physiological data in segments of 112.5 s, previous research has shown that cardiac measures can be sensitive to changes in task demand when analyzing segments of data as short as 30 s (Backs et al., 2003). There is no reason to think that the current results could not be extended to time frames as short as 30 s.

Our ability to predict the modes of autonomic control provides evidence that cardiac measures can be diagnostic as to the source of the attentional demand during task performance. If a researcher is interested in uncovering more detailed information about the psychological processes necessary for task performance, then the use of cardiac measures should be considered. For example, researchers and designers within the automotive industry might find physiological measures useful for evaluating future IVTs.

The differing sensitivity of cardiac measures relative to driving performance measures can provide information about the attentional demands of IVTs that may not be reflected by driving performance measures, thereby guarding against making incorrect conclusions about the effects of IVT design features on driver workload. In addition, the increased diagnosticity of cardiac measures can provide information about the psychological processes needed to interact with a particular IVT and how it may compete with the resources required for the primary task of driving. This information may provide a critical advantage when designing optimal IVTs.

In addition to these benefits, use of the autonomic space model may provide the researcher with a metric to assess how well users adapt to new IVTs and how attentional resource allocation strategy may change as users become more familiar with new IVTs. Therefore, an analysis of changes in autonomic space (particularly, sympathetic activity) across time may be able to be used to evaluate how well users adapt to new IVTs after they are introduced to the vehicle interior.

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