ASSESSMENT OF COGNITIVE ENGAGEMENT FROM HEART RATE DYNAMICS DURING SIMULATED DRIVING WITH AN IN-VEHICLE INFORMATION SYSTEM

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ABSTRACT

Operating a car demands sustained and flexible attention. Over recent decades, technological innovations have broadened the range of cognitive demands facing the driver. Assessing the impacts of these demands is of paramount importance for identifying safety risks and for optimizing human-machine interactions. Subjective reports are commonly used in this context but are limited in their sensitivity and time resolution. Physiology offers different a window on cognitive work loads. This investigation demonstrated unique heart-rate responses to a primary simulated driving task and to a secondary in-vehicle information system during both auditory and visual modes of information presentation.

KEYWORDS dual-task, heart rate, work load, driving simulation, LCT

INTRODUCTION

Operating a car demands sustained and flexible attention. Driving is a relatively fault intolerant environment and entails calculable risks. Over recent decades, technological innovations in communication, entertainment and navigation have broadened the range of cognitive demands facing the driver. Assessing the impacts of these demands is of paramount importance for identifying safety risks and for optimizing human-machine interactions. Subjective reports of task demands are commonly used in this context, however these are limited in their sensitivity and by their poor time resolution.

Physiology offers a different window on cognitive demands. Efficient responses to contingencies in the environment are optimized through coordinated neural and physiological reflexes. These are readily observable and in particular, characteristic heart rate responses to specific attentional and emotional engagements are well defined. What are less well defined are physiological adaptations to complex operational environments where simultaneous demands may be made on multiple cognitive processes or where selective attention is shared serially among several focal points.

Background

Control of heart rate

The beating of the heart generated by an endogenous pacemaker whose intrinsic rate is much higher than the heart rate under resting conditions. Two major neural systems shape

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the rate (and strength) of the heart, the sympathetic (SNS) and the parasympathetic (PNS). The SNS can be broadly characterized as serving the engagement of metabolically intensive challenges such as those associated with stress. A major route of SNS communication to target organs is release of chemical messengers into the blood stream. As such it is relatively slow acting and long lasting once activated. Mobilization of the SNS is associated with elevated heart rate in order to increase blood circulation, particularly to the muscles. The PNS on the other hand provides a brake on the heart pacemaker to slow its intrinsic rate and modulate SNS induced acceleration. The major mode of SNS control of the heart is though a branch of the Vagus nerve from the brain(stem) to the pacemaker. Unlike the SNS, PNS vagal nerve control of the heart is very fast. The SNS and PNS with their reciprocal effects on heart rate are always co-active with varying relative strengths depending of the state of the organism and ongoing demands from the environment. This simultaneous "accelerator" and "brake" influences on the heart allow rapid transient changes in rate to be superimposed on stable tonic levels.

Gas and Brakes It might help to analogize the SNS and PNS to the accelerator and brake systems of a car. "Stepping on the gas" (SNS) results in a acceleration from "0 to 60 in x seconds" while the brake (PNS) can slow the car from "60 to 0" in considerably less time! The heart "drives" with a foot on each pedal and can make rapid and precise changes by increasing or decreasing pressure on the brakes alone.

Reflexive heart rate responses and variability

Just as the freeway driving requires periodic adjustments in speed to accommodate sudden changes in traffic, optimal behavioral responses (*such as those demanded by busy freeway driving!*) are facilitated by the flexibility of the cardiovascular system to rapidly accommodate new demands. The magnitude of the variability of the heart is of great interest as an index of the coupling of the physiological engagement to the demand. The vagal system is optimized for initiating rapid engagements to challenges which may be signaled by changes in the sensory environment. For example, the detection of salient sensory events is typically accompanied instantaneous decreases in heart rate (orienting response) and behavioral inhibition (so evident in animals as "freezing"). This pattern is extended during sustained attention or quickly reversed when active engagement is required (e.g., flight) though the withdrawal of vagal influences. Even in the absence of episodic challenges, the heart does not beat metronomically. Rather feedback on the vagal system from cardiovascular pressure sensors impose a respiratory rhythm on heart rate and this respiratory related variability is commonly interpreted as an index of the strength of vagal control.

Relationships between cognitive workload and heart-physiological responses

That heart rate increases monotonically with mental workload is well established (e.g., [3,4,8,14,15]). That parasympathetic-vagal control of the heart is manifested in changes in heart rate variability during complex behavioral responses is also well established [12] however a clear consensus regarding the relationships between workload and the variability of the heart has yet to emerge. This is perhaps not surprising given the methodological and conceptual complexities of observing a dynamic process which may be expressed over time in distinct modes of operation.

Aims
This investigation was designed to examine short term physiological adaptations to specific challenges in a complex experimental environment. A primary driving simulator task was superposed with the operation of an in-vehicle information system which presented interactions with the driver requiring either auditory or visual attention, or both simultaneously. A key motivation for this study was developing a methodology for the assessment of cognitive workloads which could inform the future design of safer vehicle information systems and interfaces.

METHODS
This study was designed to contrast subjective and objective work loads during a primary task (simulated driving) and 1 of 3 concurrent secondary tasks related to the operation of a novel in-vehicle information system (IVIS). The background and design of the secondary task as well as analyses of subjective workloads and driving performance are discussed in more detail in a companion paper [16].

Subjects
This experiment was conducted at the University of Gothenburg's Vigilance and Neurocognition Laboratory using 14 volunteer subjects, aged 18 to 41, who had driving experience. The experiment was conducted using the English language and although none of the subjects were native speakers, we ensured that all were comfortable communicating in English.

Primary task
Driving simulation was performed using the ADAM LCT (Lane Change Test) software [7] in a modified Volvo passenger car platform. A realistic view of the roadway through the windshield is provided by a front projection system with a 120° horizontal field width. The LCT simulator logs vehicle performance parameters, including speed and lane-position, at 16.6 ms (60hz) sampling intervals and computes the vehicle's lateral deviation from a fixed template representing an "ideal" trajectory (tracking).

The LCT involves driving on a straight three-lane road segment at a target speed of 60 km/h while periodically changing to lanes designated by roadside signs. Each track segment contains 18 signs which are spaced at intervals between 140 and 188 meters. At the end of each track, the roadway continues in a U-shaped turn leading into a new track segment with a unique distribution of signs. Ten unique consecutive track segments allowed continuous driving during the self-paced performance of a secondary task.

Secondary tasks
Three secondary tasks involved operating an steering-wheel mounted internet and telephone controller (Breeze)[16] to open an email and then initiate a telephone call based on the content of the email. The tasks differed in their modes of presenting information to the user: ***Auditory*** (A) using synthesized speech , ***Visual*** (V) from a dashboard mounted LCD screen and ***Mixed*** (AV), the simultaneous presentation of both A and V .

Figure 1: Breeze controller

Outcome measures

Physiological responses

We made continuous physiological recordings at sampling rates of 200 Hz using an Embla A-10 data recorder (Flaga, Reykjavik). Heart activity (EKG) was recorded from chest electrodes in a VII derivation. The precision of the determination of the timing of EKG R-waves was enhanced to 1 ms by up-sampling. In addition, breathing was measured using chest expansion sensors and EMG from several respiratory muscle group and eye movements were recorded using both horizontal and vertical EOG.

Physiological adaptations to task engagements were indexed by the average heart rate (the interval between R-waves in milliseconds) and by the beat-to-beat variability of R-R intervals. This variability was calculated as the root mean square of successive differences of EKG R-wave intervals after trimming of the extreme 5% (2 tailed) sample values ($RMSSD_5$) [6]. In this paper, we refer to $RMSSD_5$ using the common term "heart rate variability" (HRV).

Subjective reports

Subjects rated their perceptions of experimental task associated work load in the functional domains of attentional effort, visual and auditory processing, temporal demands, task interference, and emotional stress immediately after each trial using the 6 item Driving Activity Load Index (DALI) [9,10]

Driving simulator

Driving performance was indexed by the accuracy (mean) and precision (standard deviation) of both driving speed and steering tracking to lane changes.

Procedure

The experiment was conducted in 3 phases which were self paced to ensure that the subjects felt competent and comfortable with the experimental tasks and to minimize the dimension of temporal pressure while completing each task (Figure 2). In the first phase, *training,* the subjects practiced using the Breeze controller, simulator driving and performing the LCT until they felt confident with each task. Data collection began with the next *Baseline* phase. Subjects performed each of the 3 secondary Breeze tasks without driving as well as a single trial of the LCT. In the final *dual-task* phase, completed 3 consecutive blocks consisting of simultaneous LCT and Breeze tasks followed by administration of the DALI and a 5-minute quiet rest period sitting in the car with closed eyes. The ordering of the 3 Breeze modalities was randomized across subjects.

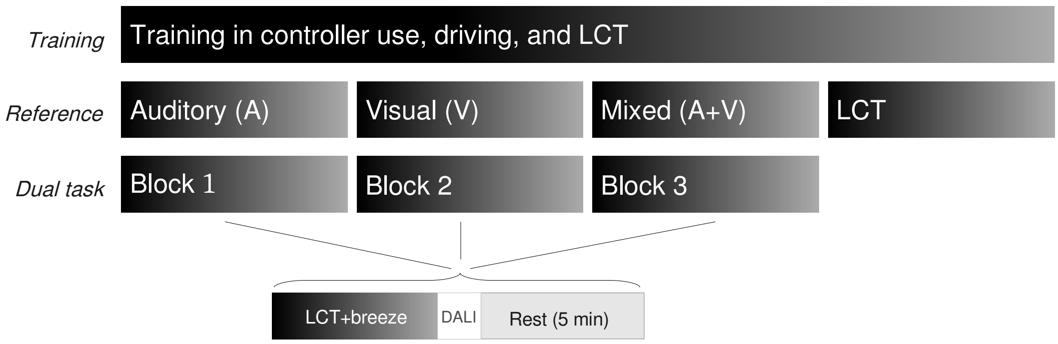

Figure 2: Sequence of experimental tasks. Note that all tasks were self paced and that the ordering of Breeze modalities was randomized across subjects in the dual task blocks.

Signal processing and Statistics

Signal processing of heart rate signals and statistical analyses were performed using software written in the R statistical language [13] with NLME library [11].

Within each Breeze modality, we estimated the contrasts between Rest, baseline-LCT, baseline-Breeze, and LCT+Breeze conditions using linear mixed effects (LME) models with the inclusion of task duration as a modeling term to control for unequal sample lengths. For ease of interpretation, we present these contrasts graphically with effects estimates and their associated p. values (2-tailed) for Wald hypothesis tests of NULL differences.

RESULTS

The time required to complete the experimental tasks (and hence the length of the physiological samples) was generally under 2.5 minutes (Table 1). Note that the duration of the combined LCT+Breeze trials were determined by completion of the Breeze task and are not comparable to the baseline LCT.

Physiological adaptations to driving Relative to rest, performance of the LCT-alone was associated with reliable increases in heart rate and decreases in HRV (figure 3).

Physiological adaptations to Breeze tasks Relative to rest, there was no evidence of cardiac adaptations to the Breeze tasks alone.

Table 1: Trial durations (seconds).

Trial	Mean	SD
Baseline LCT	183	37
Baseline Visual	111	24
LCT + Visual	145	20
Baseline Auditory	141	42
LCT + Auditory	158	50
Baseline AV	99	16
LCT + AV	137	34

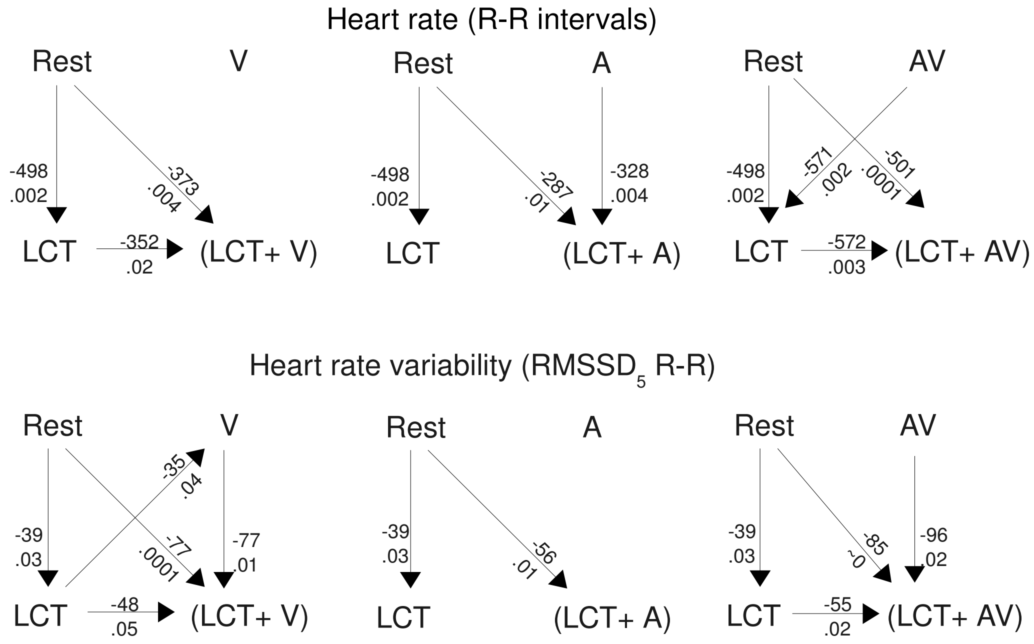

Figure 3: Contrasts among trial conditions for R-R intervals (top) and $RMSSD_5$ "heart rate variability" (bottom) by Breeze modality. The arrows indicate the direction of relative decreases in R-R intervals (i.e., increased heart rate) and HRV. The accompanying number pairs are the estimated effect (milliseconds) and P value for a Wald test of null differences. Contrasts with P values > 0.15 are not shown. Each 100 millisecond change in R-R is equivalent to to 6 heart-beats per minute.

Contrasts and interactions between primary and secondary tasks Considerable interaction between LCT and visual attention demands was apparent in the potentiation of heart rate and HRV responses between LCT-alone and <u>LCT+V</u> and <u>LCT+AV</u> dual-task trials. In addition, selective effects on HRV are seen in the contrasts between <u>V</u> and <u>LCT+V</u> and between <u>AV</u> and <u>LCT+AV</u>.

There were no differences between modalities in driving performance or in DALI ratings of stress, temporal demands, or task interference. Dali attentional loading during <u>LCT+V</u> was significantly higher than <u>LCT+A</u> or <u>LCT+AV</u> (*t 2.8, P 0.01*).

DISCUSSION

These findings suggest that cognitive demands in complex operational environments can be detected and differentiated though changes in autonomic nervous system regulation – namely the rate and the beat-to-beat variability of the heart.

We found that the primary task (alone) was associated with reliable increases in heart rate and decreases in HRV while the secondary tasks (alone) did not evoke any physiological responses. When primary and secondary tasks were combined, the 2 secondary tasks involving visual attention magnified these increases in heart rate and reductions in HRV suggesting a simultaneous increase in workload and sustained attention. DALI ratings confirmed that visual attention was a substantial component of performance during the mixed AV trials. On the other hand, the secondary task requiring auditory attention did not add to the LCT related physiological responses. While subjective work loads and objective driving performance did not manifest any task-modality related decrement, the physiological data suggest that the additional demands placed on visual attention from the need to coordinate 2 separate fields of view come with the metabolic cost of approximately 20 to 30 heart beats per minute.

The interpretation of physiological findings, and particularly of dynamical variability are crucially dependent on the nature of the experimental challenges from the perspectives of both the cognitive functions they are designed to probe and the range of strategies and emotional responses which they invoke in people. For example, as we noted earlier, engagements requiring concentration are favored by enhanced parasympathetic activation without concurrent sympathetic activation with the net effect of decreased HRV and reduced or unchanged heart rate [5]. But, even the most benign performance tasks can become onerous and stressful over time as the predominant challenge becomes the maintenance of interest [17].

Valid statistical inferences are dependent on the implicit assumption of the uniformity of observations within the sampling period. This is often difficult to achieve because physiological adaptations to new challenges can vary substantially between their beginning, middle, and end [5]. In this experiment, the relatively short (< 3 minute) task engagements helped to ensure the relative stability of physiological measurements by minimizing the depletion of resources (fatigue) and/or the decrement of attention (low vigilance, boredom) that can occur over extended performance [17].

While statistical descriptions of the variability of heart rate are usually referred to as "heart rate variability" or "HRV", a large number of different methods and lack of standardization renders HRV problematic as a unitary concept [1,2]. This investigation employed a time domain approach which reported the robust statistical variance of the differences between successive heart periods. $RMSSD_5$ is a robust short term variability which is insensitive to longer term variability which bias spectral based methods and is most suitable for relatively short data sequences.

In conclusion, we were able to distinguish between interactions of the primary task with visual and auditory modes of information processing during short-term cognitive challenges using physiological measures. In the context of interaction design, these findings suggest that secondary task relying solely on audio interaction was least taxing on attentional resources. We suggest measuring short term cardiac regulation is a practical and valuable tool for the study of cognitive engagements in complex operating environments.

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