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***A FIELD STUDY ASSESSING DRIVING PERFORMANCE, VISUAL ATTENTION,
HEART RATE AND SUBJECTIVE RATINGS IN RESPONSE TO TWO
TYPES OF COGNITIVE WORKLOAD***

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Summary: In an on-road experiment, driving performance, visual attention, heart rate and subjective ratings of workload were evaluated in response to a working memory (n-back) and a visual-spatial (clock) task. Subjective workload ratings for the two types of tasks did not statistically differ, suggesting a similar level of overall workload. Gaze concentration and heart rate showed significant changes relative to single task driving during the extra tasks and the magnitude of change was similar for both, while driving performance measures were not sensitive to the increase in workload. The results suggest high sensitivity of both gaze dispersion and heart rate as measures of workload across these two different types of cognitive demand.

INTRODUCTION

Driving is a complex psychomotor task which requires information processing, prompt decision making and timely physical reaction to rapidly changing roadway demands. Increased usage of in-vehicle systems and roadway congestion are illustrations of the many factors that result in an increase in cognitive workload for the driver. While the effect of cognitive workload on roadway safety is not well established, increased demand is related to longer reaction times (Patten, Kircher, Östlund, & Nilsson, 2004; Strayer & Drews, 2004), declines in hazard detection (Embrey, 2000; Kass, Cole, & Stanny, 2007), impaired lateral control (Embrey, 2000; Mattes, 2003), increased physiological arousal (Mehler, Reimer, & Coughlin, 2012; Mehler, Reimer, Coughlin, & Dusek, 2009), and a number of changes in visual behavior, (Recarte & Nunes, 2003; Reimer, Mehler, Wang, & Coughlin, 2012; Tsai, Viirre, Strychacz, Chase, & Jung, 2007; Victor, Harbluk, & Engstrom, 2005). Future vehicle systems are likely to monitor drivers' behaviors, eye movements and/or physiological changes to assess workload (Boer, 2000; Nabo, 2009) and adjust vehicle systems and automation to optimize the level of driver demand with the goal of minimizing the likelihood of breakdowns in primary vehicle control (Coughlin, Reimer, & Mehler, 2011). Understanding how and to what extent different workload measures vary in response to different types of cognitive activities is a key step towards developing effective workload management systems.

Ultimately, to assess driver workload, systems will need to monitor real-life engagements, such as interacting with a voice-interface or conversing on a phone. However, these activities are comprised of many different types of demand, such as listening, memory, and verbalization, each of which may differentially impact various aspects of driver workload and attention, and therefore may or may not result in a consistent changes in various measures (Recarte & Nunes,

2000; Schlorholtz & Schieber, 2006). The use of surrogate tasks having clearly defined demand properties may be useful in developing a more detailed understanding of the different components of cognitive demand. Previous work carried out by our group in a driving simulator (Mehler et al., 2009) found increases in heart rate and skin conductance level (SCL) in young adults in response to the added cognitive demand of a working memory - delayed digit-recall task (n-back). These findings were later validated in an on-road study using the same experiment protocol and again using young adults (Reimer & Mehler, 2011). In addition to the heart rate and SCL changes, an increase in gaze concentration was also found in response to the n-back task (Reimer, 2009). A larger scale on-road study was later conducted that also evaluated a broader age range including relatively healthy drivers in their 20s, 40s and 60s. Statistically significant incremental increases in heart rate and SCL were found across the age groups with each increased demand level of the n-back task (Mehler et al., 2012). Gaze concentration in response to cognitive demand of the n-back across the three age groups was also seen in this sample (Reimer et al., 2012), although the discrimination between demand levels was not as clear as that seen in the physiological measures.

While the aforementioned findings are useful, further work is needed to assess whether these patterns are unique to the n-back task or generalize across other cognitive tasks. The main objective of the present paper is to evaluate the extent to which a cognitive task that calls upon mental resources that differ from those called upon by the n-back task produce similar or divergent patterns of response. The n-back task used in the previous studies requires participants to hold single digit numbers in memory and to repeat them back verbally either immediately (0-back), after another number has been presented (1-back), or after two additional numbers have been presented (2-back). The task therefore calls upon the resources of working memory in the verbal/linguistic domain. For a comparison, a visual-spatial task, the Clock-task, (Schlorholtz & Schieber, 2006) was selected.

METHODS

Participants

The sample consisted of 36 older adults (20 males), aged 60-75 ($M=67.2$; $SD=5.3$), who enrolled in a study examining the impact of a cognitive training program on driving behavior. The data presented here was collected during a baseline drive prior to the intervention phase. All were in self-reported good health, regular drivers (driving three or more times per week), and free of police reported accidents for the past year. Recruitment was from the greater Boston area. The study was approved by MIT's institutional review board and informed consent was obtained.

Apparatus

Instrumented vehicle. Data collection was conducted in a 2010 Lincoln MKS. A FaceLab® 5.0 (Seeing Machines, Canberra, Australia) eye tracking system was installed to monitor drivers' eye movements. Vehicle dynamic data were collected at 10 Hz through the vehicle's CAN bus. A MEDAC System/3 physiology monitoring instrument (NeuroDyne Medical Corp., Cambridge, MA) was used for recording EKG at 250Hz (see Mehler, Reimer and Coughlin, 2012 for additional details on EKG recording methods and heart rate determination).

Clock Task. A visual-spatial clock task modeled after Schlorholtz and Schieber (2006) was employed. Participants were presented with a series of times as numbers, for example ‘three twenty’. Using this time, they were instructed to imagine the smaller angle between the hour hand and the minute hand on a clock face. They were instructed to answer ‘yes’ or ‘no’ to the question ‘is it less than 90 degrees or not?’ For example, as shown in Figure 1, the smaller angle between the two hands is less than 90 degrees, and therefore a correct answer would be ‘Yes’. In contrast to Schlorholtz and Schieber (2006), the stimulus sets used in the study were limited to 12, 3, 6 and 9 o’clock as a method intended to reduce confusion and demand of the task.



Figure 1. Visualization of Clock Task where 3:20 forms an angle less than 90 degrees

1-Back Task. The n-back task has been extensively used as a working memory task in automotive research (see Mehler, Reimer, & Dusek, 2011 for details). In this study, we employed the moderately difficult: 1-back level where participants listen to 30 second blocks of 10 randomly ordered digits (0-9) presented one at a time at 2.25 second intervals and are required to verbalize the digit preceding the last presented stimulus.

Experimental Protocol

Participants were trained on the two secondary tasks prior to entering the test vehicle and given additional practice in the vehicle prior to driving. The experiment was conducted on a section of highway I93 north of Boston, MA. Drivers were given approximately 20 minutes to habituate with the vehicle prior to being presented with two minutes of the clock task. Subsequently, participants reversed direction and completed two minutes of the 1-back task. Baseline data, i.e. driving without performing the secondary tasks, was collected for 2 minutes prior to each demand period. All instructions and tasks were prerecorded. A research associate was seated in the rear of the vehicle monitoring the participants’ safety and data collection. Subjective ratings of task difficulty were collected at the conclusion of the drive.

Data Analysis

All measures were analyzed across 2 minute intervals for baseline driving and the secondary task periods. Driving performance was evaluated by speed, SD speed, micro-acceleration, and fine steering wheel reversal rate. Micro-acceleration events were computed as the number of independent events with a unidirectional acceleration greater than 0.1g (independence was determined by a minimum event separation of 2 or more seconds). Reversal rates were computed using a 2° reversal gap. Horizontal and vertical gaze dispersion was calculated by projecting the driver’s angle of gaze onto a flat plane at a distance corresponding to the vehicle’s windshield and then computing a simple standard deviation of gaze points. This technique has been shown to be sensitive to changes in gaze concentration under cognitive demand (Reimer et al., 2012). Driving performance and eye movement data were analyzed across the entire subject population,

while heart rate data was assessed across 26 participants due to recording issues. Driving performance, heart rate and gaze dispersion were tested for their sensitivity for workload levels between task condition (baseline or tasking), and consistency between task types (1-Back or Clock task). Correlation tests were then conducted for the measurements shown to be sensitive to the increase of workload and demonstrated similar patterns of changes between two types of cognitive tasks, to investigate the level of agreement for these measurements.

RESULTS

Subjective workload rating and secondary task performance

Participants reported mean subjective difficulty ratings of 4.25 (SD=2.52) and 3.61 (SD=2.40), on a 1 to 10 scale where 1 is “very easy” and 10 “impossible”, for the clock and 1-back tasks respectively. The perceived difficulty of the two tasks were not statistically different ($F(1,35)=2.38, p=.13$). No significant difference in actual performance was found either ($F(1,35)=1.55, p=0.22$). Correct response rates were 86.57% (SD = 16.34%) for the clock trials and 91.44% (SD=17.67%) for the 1-back trials.

Driving performance

A MANOVA was conducted for the driving performance data due to the multiple dependent variables collected for evaluation in this domain. None of the four measures was shown to be sensitive to the increases in cognitive workload (speed: $F(1,144)=.29, p=.59$; SD speed: $F(1,144)=.22, p=.64$; micro-acceleration: $F(1,144)=2.87, p=.09$; steering wheel reversal rate: $F(1,144)=.13, p=.72$). No effect of drive segment was apparent for most measurements (speed: $F(1,144)=.56, p=.46$; SD speed: $F(1,144)=1.69, p=.20$; reversal rate: $F(1,144)=.35, p=.56$), apart from for micro-accelerations ($F(1,144)=5.63, p=.02$) where the mean values indicated that they were more common during the drive segment that included the clock task vs. the segment that included the n-back. No interaction effect was found.

Gaze concentration

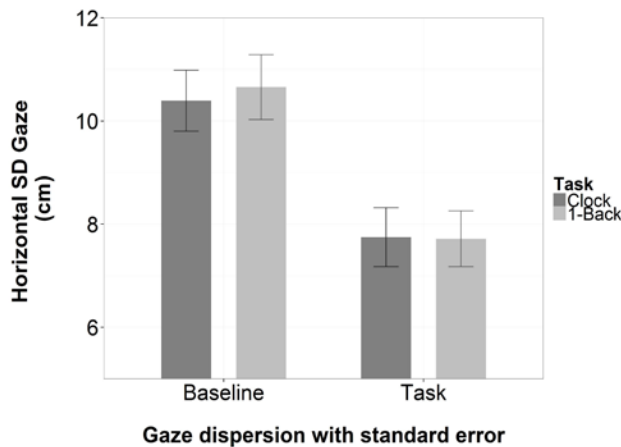


Figure 2. Horizontal gaze during single task driving and during Clock and 1-Back segments

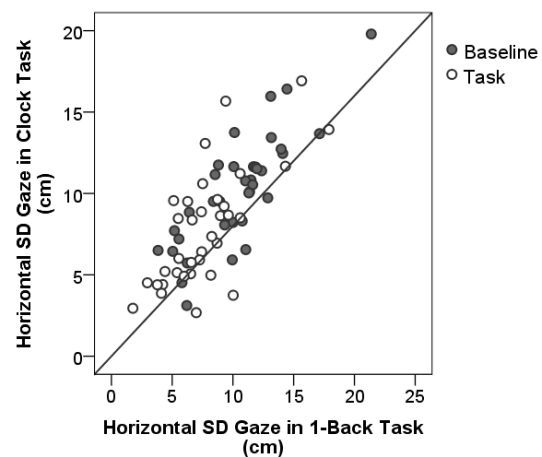


Figure 3. Correlation of SD gaze during the Clock and 1-Back segments of the drive

Reimer, Mehler, Wang and Coughlin (2012) found that horizontal gaze dispersion was sensitive to the demand of the 1-back task. Consistent with this work, a significant main effect of condition (single task driving vs. added cognitive demand) appears ($F(1,35)=37.27, p<.01$). There is no main effect of drive segment ($F(1,35)=.06, p=.81$) or interaction between workload condition and drive segment ($F(1,35)=.31, p=.58$). This is apparent in Figure 2 where horizontal gaze dispersion is quite similar during the two baseline reference periods and shows comparable concentration shift during the clock and 1-back tasks. The consistency in the relationship between the relative horizontal gaze dispersion across the two driving segments considering both baseline and demand periods can be seen in the scatter plot shown in Figure 3 (Bivariate Pearson Correlation, $r=.79, p<.001$).

Heart rate

Mehler, Reimer and Coughlin (2012) found that heart rate increased in response to the 1-back working memory task. Consistent with this, an increase in heart rate was observed with the added demands of the 1-back and clock tasks ($F(1,25)=12.78, p<.01$) in the present study. In line with observations reported above for gaze concentration, there was no main effect of drive segment ($F(1,25)=.14, p=.71$) or interaction between workload condition and drive segment ($F(1,25)=1.56, p=.22$). This can be seen in Figure 4 where no substantive differences appear in the heart rate during the two reference (baseline) periods or during the tasks. Conversely, heart rate was closely correlated when both when performing Clock and 1-back tasks and during the two single task driving periods (Bivariate Pearson Correlation, $r=.96, p<.001$) (see Figure 5).

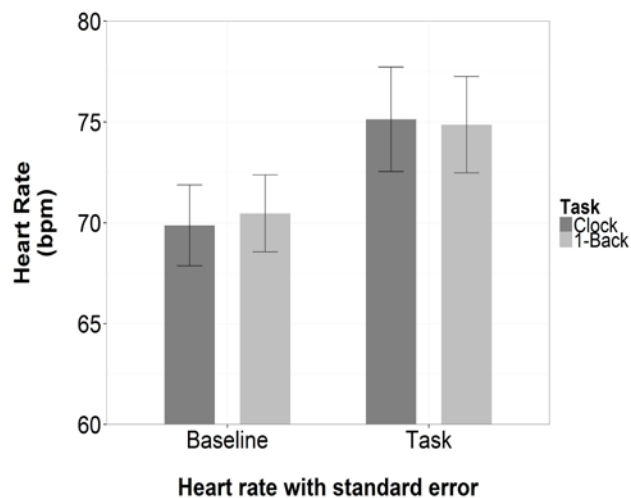


Figure 4. Heart rate during single task driving and during the Clock and 1-Back segments

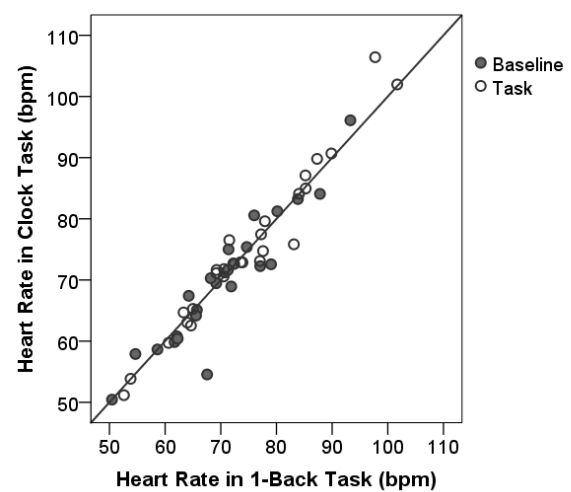


Figure 5. Correlation of heart rate during the Clock and 1-Back segments of the drive

DISCUSSION AND CONCLUSION

In this study, driving performance, heart rate and gaze dispersion were evaluated across two tasks with different neurocognitive components, i.e. visual-spatial representation and evaluation vs. working memory. Horizontal gaze dispersion and heart rate were found to be sensitive to the added demand of both types of workload. Further, the results show consistency in the magnitude of the concentration of gaze and the increase in heart rate as a result of the two cognitive

demands. None of the driving performance measurements were sensitive to changes in cognitive workload at the demand levels studied here.

A series of previous driving simulation and on-road studies considering drivers across a wide age range demonstrated that physiological measures including heart rate and SCL are sensitive to the cognitive demand induced by the n-back working memory task (Mehler et al., 2009; Reimer & Mehler, 2011; Mehler et al. 2012). In the on-road studies, concentrations in horizontal dispersion have been observed during the same tasks (Reimer, 2009; Reimer et al, 2012). While findings on the sensitivity of these measures for detecting changes in cognitive demand associated with the n-back task are quite clear, it might reasonably be asked to what extent this behavior extends to other forms of cognitive demand. This study extends these findings to another domain of cognitive processing (i.e. visual-spatial) by demonstrating significant shifts in both heart rate and gaze concentration in response to the clock task that are highly consistent with the changes seen in response to the n-back. Thus, the sensitivity of these measures as relatively non-intrusive methods of detecting cognitive demand does extend beyond working memory tasks. The extent to which this same pattern further generalizes to detecting other forms of cognitive demand requires more research.

This work should be considered in light of a number of potential limitations. The sample size is moderate and comprised of only older adults. The presentation of the clock task prior to the n-back for all participants could conceivably have resulted in an order effect in the data. However, in spite of these considerations, the pattern of behaviors observed in this study appears to provide a clear illustration of the sensitivity and consistency of eye based measures and heart rate to changes in cognitive workload.

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