HEART RATE VARIABILITY CHANGES DURING AN AUDITORY REACTION TIME TASK IN A SIMULATED DRIVING SITUATION

Michael. N.[1*], Patterson. J.[1], Dubaj. M.[1], Schier, M[1].
1. Sensory Neuroscience Laboratory, Swinburne University, Australia
* Faculty of Life and Social Sciences, Swinburne University of Technology, P.O. Box 218 Hawthorn Victoria 3122, Melbourne, Australia
Ph: +61 3 9214 4381 nmichael@swin.edu.au

ABSTRACT

This study used an auditory reaction time task to distract and mentally load participants while driving a simple track on a computer-based driving simulator. The aim was to investigate whether heart rate variability measures were sensitive to changes in demand associated with the dual task conditions. Time domain measures of heart rate variability indicated increasing task difficulty where as driving performance measures did not change or were not as sensitive. The study gives credence to using cardiac-based measures to enhance investigations into the cognitive demands placed on drivers in the real-world.

KEY WORDS

Heart Rate Variability, Driving, Secondary Task, Reaction Time, Distraction

As the number of potentially distracting devices in cars increases, there is a decrease in the attentional resources available to dedicate to the primary task of driving. Simulating distracting conditions and measuring responses provides a safe mechanism to determine how these situations alter one's ability to maintain attention while driving. With improved understanding of the impact of distraction, cars, and the devices used within them, can be designed to minimize dangers associated with distractions.

Many studies gauge the effect of a task or device by assessing vehicle-based measures which assume driving performance accurately reflects attention level. Direct measurement of physiological variables provide information about task load associated with arousal with less interference than other person-focused measures. Unlike subjective measures, once electrodes are applied, physiological variable measurement is continuous and does not require any involvement of the participant, or place any extra cognitive demand on them.

Although a large number of physiological variables may be studied to give additional information about the state of a participant, cardiac-based measures such as heart rate variability (HRV) seem especially relevant in attention/mental load/stress research due to the association of cardiovascular function and overall physiological arousal, and due to the potential relationship with cognitive overload. HRV power in the 0.1 Hz frequency band decreases with increased mental load [1, 2] and has been used to assess mental workload demands, dual task effects and different driving conditions [3-5]. It has been found to change with the difficulty of road segments during real driving [4, 6] and with secondary task involvement during simulated flying [7]. Although HRV measures have received some attention, they remain relatively unexplored in the driver distraction field, especially compared to vehicle-based measures.

Vehicle-based driving performance measures associated with lane position, speed, and steering wheel angle and reversals are commonly used to assess driving performance and have all been shown to be affected by concurrent secondary tasks. Those derived from speed and lane position are most consistently shown to be affected by secondary tasks [8-11]. Physiological measures may provide additional information about task load associated with arousal especially when linking them with these more traditional driving performance measures.

The present study examined HRV measures in association with driving performance during simulated driving while participants also engaged in an auditory secondary task.

METHOD

The driving simulator

The TORCS driving software package which has been used by others [12] was used for the driving simulation. This software (version 1.3.0) was downloaded from http://torcs.sourceforge.net/ [13] and installed under Linux on an IBM compatible PC (Altech Ariel Core Pro). The image was displayed on three 28 inch View Sonic LCD monitors (VX2835wm), with the two outside monitors angled slightly to create a more surrounding view.

A Logitech G25 force feedback steering wheel and pedals were used in combination with the TORCS software as the basis of the driving simulator.

The simulated vehicle provided realistic performance and feel, with the acceleration and maximum speed being similar to that of the real car it was based on [1.6L Volkswagen Golf Trendline: 14]. The simulator was programmed to automatically capture key driving performance measures to a file every 22 ms. Speed, throttle, brake and steering wheel position, offset from midline, and whether the car was over the speed limit were all recorded to the file. The number of steering reversals, the percentage of time spent over the speed limit, and the mean speed over the speed limit, were derived from relevant measures at a later time. The standard deviations (SD) of speed, offset from midline, throttle, brake, and steering wheel position were also calculated and used to indicate variation in these variables. In the case of variables like throttle position, the variation (SD) of the measure conveys much more information than the mean values which is why they were used.

The simulated track and scenery was purposefully simple and consisted of four straights connected by four different radii corners with only a few scattered trees and hills in the background. The length of the track was 3.517 km and all properties of the road including width, guide posts and signage complied with local standards and specifications [15-18]. Speed limits of 60 km/h, 80 km/h and 100 km/h were used on the straights and the corners had speed advisory signs associated with curve warning signs recommending speeds of 40 km/h, 60 km/h, 80 km/h and 100 km/h.

The AX task

In order to distract and mentally load participants while driving, an ‘AX’ task was developed which consisted of a semi-randomized string of letters requiring a response when the letter ‘A’ was followed by an ‘X’. A version was designed specifically for the experiment and was presented in the auditory modality to avoid interfering with the visual requirements of driving. Fingertip activated levers on the steering wheel were used by the participant to indicate a response to the AX task.

The letters used in the AX task and the duration of each letter was consistent with other auditory presentations of the same task [19, 20]. A basic 117 stimuli string of letters was created by ordering the letters in a semi-randomized fashion. This basic string consisted of 30 (25.64%) target letters (i.e. an ‘X’ which had been preceded by an ‘A’) and 87 (74.36%) non-target letters (no response required). Nine percent of the non-target letters were the letter ‘A’ but with no ‘X’ following. To ensure the AX task continued for the duration of each driving condition, the basic string of letters was repeated in a continuous loop. Thus the number of letters presented while driving was partially determined by the time the participant took to complete the driving condition.

Two inter-stimulus-intervals (ISI) were used to create two different speed versions of the AX task. An ISI of 1000 ms was used to create a slower presentation rate and an ISI of 600 ms was used to create a faster presentation rate. These two versions were arbitrarily named AX1 (slower) and AX2 (faster). Baseline performance on both levels of the AX task was determined by administering this task as a single stand-alone task. Although not the primary focus of the study this allowed comparisons between performance on the task in single (baseline: no driving) and dual task (driving) conditions.

AX task responses were analyzed in relation to presentation of the letter stimuli allowing reaction times (RT), missed targets, false positives and correct responses to be identified. RTs were only calculated for correct responses and the target was deemed to be missed if the participant had not responded before the end of the presentation of the next letter. This task requires auditory attention and short term memory. Similar cognitive processes would be required if someone was having a conversation on the phone or with a passenger while driving which make this task relevant to real world situations. As the task is auditory and does not require visual attention, it does not interfere with the visual processing required for car control and thus any distracting effects can be attributed to an increased cognitive demand rather than a struggle for visual resources.

ECG and HRV measurement and analysis

The electrocardiogram (ECG) was recorded continuously throughout the driving simulation which allowed heart rate variability (HRV) measures to be calculated. The ECG was recorded (sampled at 512 Hz) from electrodes placed in the middle of the right collar bone and just below the bottom of the left ribs. The signals were referenced to FCz (International 10-20 system electrode site) with the ground on the right mastoid. The raw ECG signal was imported into Matlab® and the R-wave component of each heart beat of the ECG was identified using the BioSig toolbox [21]. Once the R-waves had been identified their placement was checked visually using Wave software which allowed missed or extra beats to be manually corrected [22]. The resulting R-R interval data was imported into Kubios HRV 2.0 software for analysis [23]. Mean R-R interval, standard deviation of R-R interval (SD RR), percentage of beats that differ by more than 50 ms (pNN50) and absolute LF power (0.1 Hz component) were calculated separately for each participant and each driving condition.

Procedure

A total of 50 participants (25 men, 25 women) aged from 19-48 years (mean: 25.9, standard deviation: 5.6) completed the study. All gave written informed consent to the study which had been approved by the University Human Research Ethics Committee. After having the electrodes required for ECG measurement attached, participants were given a practice on the driving simulator. They were instructed to drive two full laps of the track in order to familiarize themselves with the track and simulated car.

Once participants felt comfortable with the simulator, they remained seated and baseline performance on AX1 and AX2 was established. Participants then began the driving component of the study which consisted of three driving conditions, each lasting for three full laps of the track. The first condition involved normal driving (no-task). The second and third conditions involved driving while also responding to the slower AX1 and faster AX2 tasks respectively. Participants were instructed to drive as they normally would on a real road, and to obey the road rules and the speed limits displayed.

RESULTS

AX task performance

All results were entered into the statistical package SPSS version 16 for Windows. For AX task performance during driving one-way analysis of variance (ANOVA) were performed with driving condition (AX1 versus AX2) as the within-subjects factor. Descriptive statistics for all AX task performance variables are shown in Table 1.

Table 1. Descriptive statistics for AX task performance

	Baseline Level 1 AX		**Baseline Level 2 AX**		**Driving Level 1 AX**		**Driving Level 2 AX**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Reaction time	0.50	0.11	0.45	0.09	0.50	0.08	0.46	0.08
Percentage of correct responses	99.03	2.79	98.48	4.88	96.78	3.75	94.05	6.03
Percentage of false positives	0.28	1.17	0.28	0.94	2.22	2.07	2.85	2.37
Percentage of missed targets	1.10	2.91	1.59	4.94	3.22	3.75	5.95	6.03

N = 50

When the AX task was performed during driving there was a significant effect of level on mean RT, percentage of correct responses, percentage of false positives and percentage of missed targets ($p = 0.000$, $p = 0.000$, $p = 0.027$, $p = 0.000$ respectively). This indicated when the AX task was performed during driving, AX2 had significantly shorter RTs, fewer correct responses, more false positives and more missed targets than AX1.

In the baseline measurement of the AX task alone there was no significant difference in the percentage of correct responses, false positives or missed targets between AX1 and AX2 ($p = 0.43$, $p = 1.00$, $p = 0.50$ respectively). RTs were once again shorter with AX2 compared to AX1 in this baseline condition ($p = 0.000$).

When performance of the AX task during driving was compared to the baseline measurement the percentage of correct responses decreased, and the percentage of false positives and missed targets increased for both levels of the AX task (all p values = 0.000). RTs between conditions did not differ significantly (AX1 $p = 0.94$, AX2 $p = 0.20$).

HRV

For the HRV and driving performance variables a one-way (ANOVA) was performed with driving condition (no-task, AX1, AX2) as the within-subjects factor. Where significant effects were found, repeated within-subjects contrasts were performed (no task vs AX1, and AX1 vs AX2). Descriptive statistics for the HRV and driving performance variables are shown in Table 2.

Table 2 Descriptive statistics for HRV, HR and driving performance measures

	Driving No secondary task		Driving AX1		Driving AX2	
	M	**SD**	**M**	**SD**	**M**	**SD**
Mean RR interval	811.16	112.49	798.66	111.11	788.40	109.50
Variation in RR interval	54.36	23.40	49.91	19.72	49.81	18.58
pNN50	17.83	16.81	16.78	16.38	14.69	14.72
Absolute low frequency power	1235.74	1736.25	1115.28	1211.95	1104.96	1086.82
Mean speed	75.96	7.56	76.14	7.55	76.90	8.04
Variation in speed	18.41	2.26	17.23	2.59	17.51	3.02
Mean offset from midline	0.42	0.18	0.43	0.23	0.44	0.23
Variation in offset from midline	0.29	0.13	0.30	0.17	0.31	0.18
Variation in throttle	0.26	0.05	0.25	0.05	0.27	0.05
Variation in brake	0.03	0.01	0.03	0.01	0.03	0.01
Variation in steering	0.01	0.00	0.01	0.00	0.01	0.00
No. of steering reversals	298.56	119.70	328.20	198.71	316.68	149.43
Percent over speed limit	21.00	15.43	19.05	14.72	20.90	15.19
Mean over speed limit	4.16	2.75	3.74	2.31	4.06	3.00

N = 50 for all variables except mean over speed limit where N = 48

Mean RR interval was found to decrease significantly across driving condition (p = 0.000) with both the decrease from no-task to AX1 and from AX1 to AX2 being significant (p = 0.000 for both). The variation in RR intervals (SD RR) was also affected significantly by driving condition (p = 0.000). Within subjects contrasts revealed that the decrease in SD of RR from no-task to AX1 was significant (p = 0.000), however the additional decrease from AX1 to AX2 was not statistically significant (p = 0.94).

For pNN50, there was a significant decrease with driving condition (p = 0.000), with both the decrease from no-task to AX1 and from AX1 to AX2 being significant (p = 0.037 and p = 0.001). Although absolute LF power of HRV decreased slightly across driving condition the effect was not significant (p = 0.58).

Driving performance

The variation in speed (SD speed) was significantly affected by driving condition (p = 0.000). Within-subjects contrasts revealed that the decrease in SD of speed from no-task to AX1 was significant (p = 0.000), however, there was no significant difference in the SD of speed between AX1 and AX2 (p = 0.37). There was also a significant effect of driving condition on the variation in throttle (SD throttle) (p = 0.001). Within-subjects contrasts showed there was a significant increase in the SD of throttle from AX1 to AX2 (p = 0.000) but there was no difference between no-task and AX1 (p= 0.198).

No significant effects due to driving condition were observed on mean speed, mean offset from midline, variation in offset from midline (SD offset midline), variation in brake (SD brake), variation in steering (SD steering), number of steering wheel reversals, the percentage of time spent over the speed limit and the mean speed when over the speed limit (p = 0.098, p = 0.629, p = 0.166, p = 0.164, p = 0.387, p = 0.151, p = 0.113, p = 0.459 respectively).

DISCUSSION

Performance of the AX task during driving was worse when performing AX2 compared to AX1 when false positives, missed targets and the percentage of correct targets are considered. RTs however, were shorter in AX2 compared to AX1 during both driving and baseline conditions. Additionally, there was no difference in RTs (for either level of the AX task) from when the task was performed alone as a single task to when it was performed as a dual task while driving. This shows that the time required to respond to a target letter once identified was the same whether the AX task was performed alone or in combination with driving. The impairment associated with performance of this task, when performed as a dual task, was related to the perception of the letters and the decision making process as to whether or not a letter required a response. The shorter RTs associated with AX2 compared to AX1 were most likely attributed to the shorter inter-stimulus interval as it has been reported that increasing the ISI increases RTs [24, 25]. This quicker ISI also resulted in AX2 being more demanding than AX1 as reflected by the increased number of errors for AX2 compared to AX1. Thus in all further discussion the AX2 driving condition is considered more difficult than the AX1 driving condition.

All of the time domain measures of HRV changed significantly with driving condition. Mean RR interval and pNN50 differed between all three driving conditions, where the SD of RR only differed between task and no-task driving conditions. Our results suggest that time domain measures of HRV indicate changing driving demands. Unfortunately such measures have usually been neglected when exploring mental load while driving as the majority of studies focus on 0.1 Hz component of HRV. Such studies report changes with increasing task or driving difficulty [4, 6], and although these measures do not always differ between task levels, they often differentiate between task and no-task conditions [26, 27]. Our frequency analysis, however, did not show any significant differences between any of the driving conditions.

The finding that the time domain measures of HRV were sensitive to task load where the 0.1 Hz component was not contrasts to commonly held views of the 0.1 Hz frequency band being the most sensitive HRV measure and being able to indicate changes in mental load at levels where other HRV measures can not [5]. Although our recording duration of the ECG is considered adequate for frequency analysis of HRV [28] the sampling frequency of the ECG was limited by recording equipment and is at the lower end of recommended ideal rates [28, 29]. This may have influenced the ability to detect changes in the frequency analysis. More recently, Cowan [30] has reported that frequency domain measures are poor for short data sets, and taken with present findings potentially suggest that time domain measures of HRV might be more worthwhile than previously thought.

Overall, driving performance remained relatively stable despite concurrent performance of an auditory secondary task. The majority of the driving performance measures were not affected by the simultaneous performance of the AX task at either level. Only the SD of speed and SD of throttle were significantly affected by driving condition with the SD of speed differing between no-task and AX1 and the SD of throttle differing between AX1 and AX2. None of the driving performance measures differed between all three driving conditions. The lack of change in driving performance associated with secondary task performance is in contrast to previous studies [9, 31, 32]. The related measures of SD of speed and SD of throttle indicated a change in speed control of the car with secondary task performance. While a change in speed control with secondary task performance is consistent with other studies, in our results, that change was in the opposite direction to the majority of reports [10, 31].

In this experiment, both the primary driving task and the secondary task were low demand tasks. Despite the ease of performing such tasks alone, and the relative ease of performing the tasks together, when combined, cognitive load increased. It seems that the performance of the AX task was sacrificed in order to maintain the primary visual task of driving. This is not surprising given the subtly implied priority of the driving task in the directions given to participants (see method). This increased load associated with AX task performance was more consistently detectable with time domain HRV measures than standard driving performance measures. The changes in the physiological measures paralleled those occurring in performance of the AX task. Although there were signs of driving performance deteriorating, these measures did not follow the same general pattern associated with increasing demand like the HRV and AX measures indicating that vehicle-based measures do not always accurately reflect attention level.

The time domain measures of HRV showed a quickening of the heart beat, and a more regular heart beat with less variability. Such a shift in autonomic tone towards increased sympathetic activity can normally be related to one of two physiological conditions: either increased physical workload or increased mental workload or stress. The fact that no, or minimal, physical effort was required to press the lever on the steering wheel verifies that the changing driving conditions associated with the secondary task resulted in a higher cognitive demand/stress placed on the driver. The use of heart rate based physiological measures which are related to easily understood physiological control systems makes interpretation of such results reasonably clear and avoids some of the ambiguity which can occur with driving performance measures i.e. a decrease in speed and variability of speed could be interpreted to indicate greater attention being paid to speed maintenance or alternatively a lack of attention to speed control.

The ease of measuring such physiological variables without placing additional demand on a driver makes these measures very useful when studying attention and distraction within a vehicle. These results suggest it may even be possible to use physiological variables to indicate task load without actually measuring task load, or in situations where it is not actually possible to quantify task load. Additionally, such variables may help to differentiate between more subtle variations in driving demand when such changes are not evidenced by changes in driving performance or when changes are minimal.

The demand on auditory attention and short term memory required in the present study makes these findings relevant to real-world driving situations where an increase in auditory signal processing is occurring. The increasing use of auditory based devices such as MP3 players, GPS systems and mobile phones, combined with the more traditional auditory distractions such as the radio and passengers, leads to a variety of auditory signals to be attended to, perceived, and often responded to. The combination of such auditory signals along with the regular demands of driving may lead to significant increases in cognitive load, as observed in the present study. Even if driving performance has not deteriorated, if a person is sufficiently cognitively loaded through interaction with other tasks it is possible that unpredictable or unexpected situations may not be able to be dealt with adequately which can have dangerous consequence in real driving.

These results are important as they demonstrate physiological and performance changes despite the use of low-demand and low-stress driving and secondary tasks. Even though the secondary task was auditory and did not interfere with the visual processing required for car control, participant’s ability to cope decreased with increasing task load. Physiological measures suggested a change in sympathetic autonomic nervous system towards greater arousal, with time domain measures of HRV paralleling task difficulty during driving. The cardiac-based measures were better able to discriminate between task levels than driving performance measures which were barely impacted. The tasks studied here are less demanding than many tasks undertaken in real-driving by drivers and the sensitivity of cardiac-based measures in these situations indicate that such measures may be used to enhance investigations into the demands placed on drivers in the real-world. We recommend the inclusion of such measures in future driving distraction research.

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