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

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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 the 0.1 Hz component of heart rate variability (HRV) was sensitive to the changes in demand created by these relatively simple dual task conditions. Performance on the secondary task appeared to be sacrificed in order to maintain relatively stable driving performance. The 0.1 Hz component of HRV did not reflect the increased demands associated with the dual task conditions, whereas the time domain measures of HRV did.

KEY WORDS

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

Driving a vehicle is a common daily activity for many people in developed nations. Unfortunately, driving is not the only task people engage in while driving. The use of mobile phones, conversations with passengers and interactions with navigation or infotainment systems are some of the many other tasks that are commonly combined with driving [1, 2]. These momentary or continuous distractions can decrease the attentional resources available for the primary task of driving. Measuring attention to, or distraction from, the primary driving task is critical to understanding how such secondary tasks impact driver performance. Many studies gauge the effect of a task or device by assessing vehicle-based measures. This approach assumes that driving performance accurately reflects attention level. Direct measurement of physiological variables can also be used to provide information about a person's state. The relationship between selected physiological measures and driver load is investigated in this study.

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 [3-6]. Although it has been suggested that physiological variables may be able to give additional information about driver state, and have the potential to increase the sensitivity of studies investigating mental load in vehicles [7], the number of investigations incorporating these suggestions is minimal.

A large number of physiological variables may be studied to give additional information about the state of a participant [7, 8], but cardiac-based measures such as heart rate variability (HRV) seem especially relevant in driving attention/load research. The association of cardiovascular function with overall physiological arousal, and the potential relationship with cognitive overload, makes HRV an appealing measure. HRV power in the 0.1 Hz frequency band decreases with increased mental load [9, 10] and has been used to assess mental workload demands, dual task effects and different driving conditions [11-13]. It has been found to change with the difficulty of road segments during real driving [12, 14] and with secondary task involvement during simulated flying [15].

The 0.1 Hz frequency band is generally described as the most sensitive of the available HRV measures [10, 13]. It has been described as being able to indicate changes in mental load at levels where other HRV measures can not [13]. Such opinions have probably led to the tendency to solely rely on this measure of HRV when studying mental load and the failure to report other (time domain) measures of HRV. Although HRV (mainly the 0.1 Hz component) has received some attention in driving studies, it remains relatively unexplored in dual-task driving research, especially when compared to vehicle-based measures. Reports of a paradigm combining numerous HRV measures with more traditional driving performance measures during dual-task driving has not been found. Additionally, although HRV clearly changes with mental load it is unclear how this measure would react to subtle alterations in load while driving a simulator.

In the present study participants drove a simple, yet involved, driving simulator. Driver load was manipulated by the use of an auditory reaction time task performed as a continuous dual task while driving. The aim of the study was to investigate whether the 0.1 Hz component of HRV was sensitive to the changes in demand created by these relatively simple tasks. It was hypothesized that the 0.1 Hz component of HRV would decrease from normal (baseline) driving conditions when driving was combined with simultaneous performance of the auditory secondary task due to an increase in mental load. Other time domain measures of HRV, studied for comparison, were not expected to be as sensitive to the mental load changes as the 0.1 Hz component as suggested by others [13]. Driving and secondary task performance were also measured for comparison. This study with its relatively simplistic dual-task demands and rather predictable outcomes was also designed for the purpose of benchmarking the physiological and driving performance measures so that comparisons with a more involved study could be made at a later date.

METHOD

The driving simulator

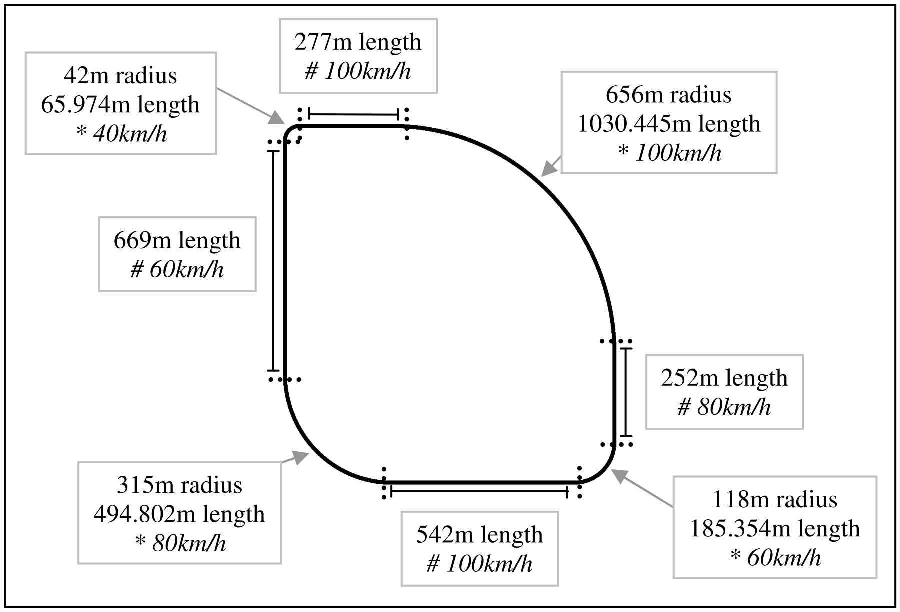
The TORCS driving software package, which has been used by others [16, 17], was chosen for the driving simulation. This software (version 1.3.0) was downloaded from http://torcs.sourceforge.net/ [18] and installed under Linux on an IBM compatible PC (Altech Ariel Core Pro). The image was displayed on 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 on which it was based (Volkswagen Golf Trendline [19]). The TORCS software was configured to automatically capture key driving performance measures which are saved to a file every 22 ms. Speed, throttle, brake and steering wheel position, lane position (absolute position of the middle of the car from the middle of its lane), 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 were designed to be simple, but varied enough to avoid being too monotonous. The track consisted of four straight segments of road connected by four corners of different radii (Figure 1). The background consisted of hills and a few scattered trees. There were no other vehicles on the road. The length of the track was 3.517 km with two 3.5 m wide lanes. It was important that the track was long enough to ensure adequate HRV data would be available for each driving condition.

All properties of the road including width, and guide post and signage design and location complied with local Victorian road standards and specifications [20-23]. Speed limits of 60 km/h, 80 km/h and 100 km/h were used on the straights and the corners had curve speed advisory signs recommending speeds of 40 km/h, 60 km/h, 80 km/h and 100 km/h. The curve speed advisory signs for the various corners were based on the speed recommended in Australia for a corner with such a radius [20]. The speed limits on the straights were 20 km/h higher than that recommended for each corner (apart from the 100 km/h corner which was proceeded by a 100 km/hr straight) which meant participants were required to adjust their speed to accurately navigate the track. This speed variability and the different radii of the corners meant participants were more involved in the driving task, thereby increasing their required attention.

Figure 1. Simulated Track Properties



\# symbolizes a speed limit
* symbolizes the posted recommended speed for the corner

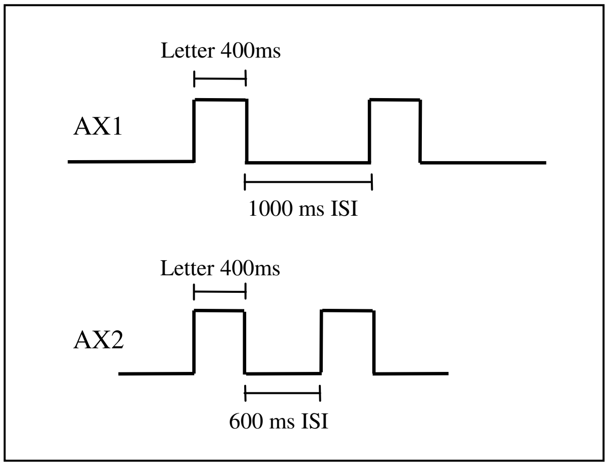
The AX task

In order to distract and mentally load participants while driving, an 'AX' task [24] was developed which consisted of a semi-randomized string of letters requiring a response when the letter 'A' was followed by an 'X'. Fingertip activated levers on the steering wheel were used by the participant to indicate a response to the task. A version of the AX task was designed specifically for the experiment and was presented in the auditory modality to avoid directly competing with the visual resources required for driving.

The letters used in the AX task (A, C, E, F, H, J, L, R, S, V, W, X, and Z) and the duration of each letter (400ms) were consistent with other auditory presentations of the same task [25, 26]. A basic 117 string of letters was created by ordering them 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). See Figure 2 for illustration of the stimulus duration and ISI of each level. During the driving conditions an average of 368 (SD = 44) letters were presented at the AX1 level and an average of 510 (SD = 63) letters were presented at the AX2 level.

Figure 2. AX task Presentation



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. The basic 117 letter string described above was presented at both speeds (AX1 and AX2) in this baseline condition.

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. The target was deemed to be missed if the participant had not responded before the end of the presentation of the next letter, and any other response was classified as a false positive. Because of this classification of responses, the reaction times measured in this study reflect when the participants are still managing the task, although potentially at a slower than 'normal' rate. The percentage of correct targets, missed targets and false positives give a better indication of the participants' ability to deal with the task.

Although the AX task is quite artificial, the task requires auditory attention and short term memory. Similar cognitive processes would be required if someone was having a conversation while driving (either telephone or with a passenger) which makes this task relevant to real world situations. As the task is auditory and does not require visual attention, it does not interfere structurally [27, 28] 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

Continuous ECG (electrocardiogram) 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 [29]. 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 [30]. The resulting R-R interval data was imported into Kubios HRV 2.0 software for analysis [31-33]. Standard measures used to assess HRV [34, 35] were generated for each participant and each driving condition using the Kubios HRV software. These measures included the mean R-R interval (mean RR), 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, measured between 0.04 - 0.15 Hz).

The amount of data used to calculate HRV has been reported to be critical to ensure accurate calculation of the various measures. Recommendations suggest a minimum ECG recording time of five minutes and also equal length recordings for each participant [34, 36]. The minimum time any one participant spent in any of the three driving conditions in this study was seven minutes and fifteen seconds. Thus seven minutes of R-R interval data were used to calculate the HRV measures for each driving condition for each person. This ensured both the minimum and equal length data recommendations were met.

Procedure

A total of 50 participants (25 men, 25 women) aged from 19-61 years (mean: 26.7, standard deviation: 7.5) completed the study. All gave written informed consent to participate in the study which had been approved by the University Human Research Ethics Committee. After ECG electrodes were attached to the participant, they 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 at the steering wheel and were introduced to the AX task. It was explained that a series of letters would be spoken through the computer speakers and that they were required to press the fingertip activated levers on the steering wheel every time they heard the letter sequence 'A X'. Pressing of the levers was demonstrated by the experimenter. Participants listened to the task and had a practice responding to a few letters. Most participants grasped the concept of the task very easily, however, if any participant seemed unsure, additional instruction and practice was given until they understood. They were then instructed that they would perform the task on its own (without driving) which is when 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. They were also told that they would be required to respond to the AX task while driving and that it would begin automatically after they completed their third lap of driving and that after three more laps the letters would be presented faster. Once again they were instructed to respond with the fingertip activated levers every time they heard the letter sequence ‘A X’.

All data were entered into the statistical package SPSS version 16 for Windows. For AX task performance during driving (dual task condition) one-way analysis of variance (ANOVA) was performed with AX level (AX1 versus AX2) as the within-subjects factor. The same analysis was performed for AX task performance during baseline measurement (single task condition). Performance of the AX task was also compared across conditions (baseline versus driving) with a one-way ANOVA performed for each level of the AX task.

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 versus AX1, and AX1 versus AX2).

RESULTS

Descriptive statistics for all AX task performance variables are shown in Table 1. Table 2 contains the descriptive statistics for the HRV and driving performance measures.

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 (s)	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

AX task performance

When the AX task was performed during driving there was a significant effect of level on mean RT (Wilks’ Lambda = 0.62, F(1, 49) = 30.66, p = 0.00), percentage of correct responses (Wilks’ Lambda = 0.60, F(1, 49) = 32.38, p = 0.00), percentage of false positives (Wilks’ Lambda = 0.90, F(1, 49) = 5.21, p = 0.03) and percentage of missed targets (Wilks’ Lambda = 0.60, F(1, 49) = 32.38, p = 0.00). 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 (Wilks' Lambda = 0.99, F(1, 49) = 0.64, p = 0.43), false positives (Wilks' Lambda = 1.00, F(1, 49) = 0.00, p = 1.00) or missed targets (Wilks' Lambda = 0.99, F(1, 49) = 0.45, p = 0.50) between AX1 and AX2. RTs were once again shorter with AX2 compared to AX1 in this baseline condition (Wilks' Lambda = 0.63, F(1, 49) = 29.16, p = 0.00).

When performance of the AX task during driving was compared to the same level of the AX task during baseline measurement the percentage of correct responses decreased (AX1 Wilks' Lambda = 0.76, F(1, 49) = 15.37, p = 0.00) (AX2: Wilks' Lambda = 0.72, F(1, 49) = 18.67, p = 0.00) and the percentage of false positives (AX1: Wilks' Lambda = 0.56, F(1, 49) = 38.68, p = 0.00) (AX2: Wilks' Lambda = 0.48, F(1, 49) = 52.78, p = 0.00) and missed targets increased (AX1: Wilks' Lambda = 0.78, F(1, 49) = 13.90, p = 0.00) (AX2: Wilks' Lambda = 0.73, F(1, 49) = 18.01, p = 0.00) for both levels of the AX task. RTs between conditions did not differ significantly for AX level 1 (Wilks' Lambda = 1.00, F(1, 49) = 1.00, p = 0.94) or AX level 2 (Wilks' Lambda = 0.97, F(1, 49) = 1.73, p = 0.20). To summarize this, AX task performance showed fewer correct responses, more false positives and more missed targets in the driving condition than in the baseline (no driving) condition. The reaction times were not significantly different between driving and baseline conditions. This was true for both levels of the AX task.

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 (ms)	811.16	112.49	798.66	111.11	788.40	109.50
Variation in RR interval (ms)	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 (ms^2)	1235.74	1736.25	1115.28	1211.95	1104.96	1086.82
Mean speed (km/h)	75.96	7.56	76.14	7.55	76.90	8.04
Variation in speed (km/h)	18.41	2.26	17.23	2.59	17.51	3.02
Mean offset from midline (m)	0.42	0.18	0.43	0.23	0.44	0.23
Variation in offset from midline (m)	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 (km/h)	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

* These variables are measured from 0 - 1.1 where 0 = off and 1.1 = on/fully depressed

$^+$ For this variable 1 unit = 540°

HRV

Mean RR interval was found to decrease significantly across driving condition (Wilks' Lambda = 0.44, F(2, 48) = 31.07, p = 0.00) with both the decrease from no-task to AX1 (F(1,49) = 22.467, p = 0.00) and from AX1 to AX2 (F(1,49) = 16.76, p = 0.00) being significant. The variation in RR intervals (SD RR) was also affected significantly by driving condition (Wilks' Lambda = 0.72, F(2, 48) = 9.45, p = 0.00). Within subjects contrasts revealed that the decrease in SD of RR from no-task to AX1 was significant (F(1,49) = 19.30, p = 0.00), however the additional decrease from AX1 to AX2 was not statistically significant (F(1,49) = 0.01, p = 0.94).

For pNN50, there was a significant decrease with driving condition (Wilks' Lambda = 0.72, F(2, 48) = 9.25, p = 0.00), with both the decrease from no-task to AX1 (F(1,49) = 4.62, p = 0.04) and from AX1 to AX2 (F(1,49) = 12.80, p = 0.00) being significant. Although absolute LF power of HRV (0.1 Hz component) decreased slightly across driving condition the effect was not significant (Wilks' Lambda = 0.98, F(2, 48) = 0.55, p = 0.58).

Driving performance

The variation in speed (SD speed) was significantly affected by driving condition (Wilks' Lambda = 0.66, F(2, 48) = 12.18, p = 0.00). Within-subjects contrasts revealed that the decrease in SD of speed from no-task to AX1 was significant (F(1,49) = 24.60, p = 0.00), however, there was no significant difference in the SD of speed between AX1 and AX2 (F(1,49) = 0.81, p = 0.37). There was also a significant effect of driving condition on the variation in throttle (SD throttle) (Wilks' Lambda = 0.74, F(2, 48) = 8.24, p = 0.00). Within-subjects contrasts showed there was a significant increase in the SD of throttle from AX1 to AX2 (F(1,49) = 16.78, p = 0.00) but there was no difference between no-task and AX1 (F(1,49) = 1.70, p = 0.20).

No significant effects due to driving condition were observed on mean speed (Wilks' Lambda = 0.91, F(2, 48) = 2.44, p = 0.10), mean offset from midline (Wilks' Lambda = 0.98, F(2, 48) = 0.47, p = 0.63), variation in offset from midline (SD offset midline) (Wilks' Lambda = 0.93, F(2, 48) = 1.87, p = 0.17), variation in brake (SD brake) (Wilks' Lambda = 0.93, F(2, 48) = 1.88, p = 0.16), variation in steering (SD steering) (Wilks' Lambda = 0.961, F(2, 48) = 0.97, p = 0.39), number of steering wheel reversals (Wilks' Lambda = 0.92, F(2, 48) = 1.97, p = 0.15), the percentage of time spent over the speed limit (Wilks' Lambda = 0.91, F(2, 48) = 2.28, p = 0.11) or the mean speed when over the speed limit (Wilks' Lambda = 0.97, F(2, 46) = 0.79, p = 0.46).

DISCUSSION

Performance of the AX task during driving was worse for AX2 than AX1 when false positives, missed targets and the percentage of correct targets are considered. All of these errors were higher for AX2 than AX1 when driving. RTs however, were shorter in AX2 compared to AX1 during both driving and baseline conditions. This difference is not surprising and is most likely due to the presentation properties of the task. Larger inter-stimulus intervals have been reported to lead to increases in RTs [37, 38] and thus the shorter ISI associated with AX2 compared to AX1 was likely to foster quicker responses. No differences in AX task RTs were found between the task when performed alone as a single task, or in combination with driving (for both levels of the AX task). This is likely due to the fact that RTs were only calculated for correct responses, which is when participants were managing the task. The impairment associated with 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. Overall, the shorter ISI associated with AX2 resulted in it 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.

For the HRV analysis, the absolute LF power (0.1 Hz component) did not show any significant differences between any of the driving conditions. This is in contrast to previous research that reports changes with increasing task or driving difficulty [12, 14]. Although this measure does not always differ between task levels, it typically differentiates between task and no-task conditions [39, 40]. In contrast to these frequency domain results, 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 differed between task and no-task driving conditions.

The finding that the time domain measures of HRV were sensitive to task load, where the 0.1 Hz component was not, contradicts commonly held views of HRV measures. It was no real surprise that a change in physiological state occurred when greater demands were placed on the mental workload of the driver, it was just unexpected that the 0.1Hz component did not pick up these changes and other HRV measures did. The 0.1 Hz frequency band is generally described as the most sensitive of the HRV measures, being able to indicate changes in mental load at levels where other HRV measures can not [13]. Unfortunately, time domain measures have usually been neglected when exploring mental load while driving, as the majority of studies focus on 0.1 Hz component of HRV due to these reported advantages of the measure. The present findings 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 [4, 41, 42]. 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 [5, 41].

In this study the AX task provided numerous indicators of performance and acted as a cognitive/mental distraction without having the ‘eyes off the road’ type distraction associated with other secondary tasks. The demand on auditory attention and short term memory produced by the AX task makes the findings of the study 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 mental load, as observed in the present study.

As far as dealing with the increased load imposed on participants in this study, performance of the AX task appeared to be sacrificed in order to maintain the primary visual task of driving. It is also possible that participants invested extra effort to maintain driving performance at the same level. 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.

This study has established that even a relatively easy auditory task, when performed during driving, can increase mental load despite no behavioral evidence (driving performance) of this. Such a change in driver load was detectable with time domain measures of HRV and indicates that vehicle-based measures do not always accurately reflect attention level. The time domain measures of HRV showed a quickened and more regular heart beat with secondary task performance, which indicates a shift in autonomic nervous system tone towards increased sympathetic activity (greater physiological arousal). The ease of measuring and analyzing such physiological variables which are related to easily understood physiological control systems, and the ability to obtain them without placing additional demand on a driver, makes these measures very useful when studying attention and distraction within a vehicle.

The combined use of physiological and driving performance measures in driver distraction research is rarely utilized. The current findings give support to suggestions that physiological measures can give additional information about driver state, and have the potential to increase the sensitivity of studies investigating mental load in vehicles [7]. The present study also builds on previous research by incorporating numerous measures of HRV within the one study rather than the reliance on just one. This proved to be worthwhile as changes occurred in some, but not all, HRV measures. If only the frequency domain 0.1Hz component of HRV had been measured one could have concluded that no change in physiological state had occurred. Additionally, the focus of the present study on relatively small alterations in driver load has demonstrated that time domain measures of HRV may help to differentiate between more subtle variations in driving demand when such changes are not evidenced by driving performance measures or when changes are minimal. An additional measure to further enhance future studies may be the inclusion of subjective ratings of load.

The physiological and driving performance results from this study will serve as a benchmark for future studies utilizing the TORCS driving simulation software in combination with other secondary tasks. The results from the planned, more involved, study will be able to be directly compared with the results of the present simplistic study. It is envisaged that this will aid interpretation and help to put perspective on the results associated with a more complicated experimental design.

The conditions in this study were not counterbalanced, thus some practice effects were expected to occur. Although participants would have become more familiar with performing the AX task, it is unrealistic to imagine that they would have been able to increase their performance much by memorizing it, or segments of it, due to the length of the base string of letters (117) and the repeated and semi-random use of the same letters within this string. Practice effects would have been more likely associated with driving the same route. Although this may have slightly reduced the negative impact of the AX task on driving, mental load was still predicted to increase across conditions which was considered sufficient for the study.

It would be interesting to examine the effects of the secondary task in relation to different segments of the driving route (i.e. the different speed zones or different curvatures of the track); however, the analysis requirements of the 0.1 Hz component of HRV (frequency domain) stipulated a minimum of 5 minutes of ECG data for accurate calculation of the measure. As this measure was the focus of the study and required long segments of data, secondary task effects were not examined for the shorter sub-sections of track. Future work could investigate the effect of the dual task depending on the difficulty of the track segments using time domain measures of HRV. Such measures of HRV can be assessed over shorter periods of time and proved to be sensitive to changing driving load in this study.

An ideal end result of dual-task driving studies is to identify when the increase in load compromises driving safety. This requires using some criterion of the level of performance decrements, or physiological arousal, and deciding what level of change is unacceptable. Given that the type of secondary task or distraction while driving affects various driving performance and physiological measures differently, it seems questionable that a single measure could be applied to all situations. As far as HRV measures are concerned, the relative lack of studies utilizing this measure in driving makes such a task unrealistic at this point in time.

The results of the present study are important as they demonstrate physiological and performance changes despite the use of low-demand and relatively easy 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. Performance of the secondary task was sacrificed in order to preserve the primary task of driving. Contrary to expectations, the 0.1Hz component of HRV was not sensitive to the increased load associated with secondary task performance. However, time domain measures of HRV suggested a change in sympathetic autonomic nervous system tone towards greater physiological arousal, with such measures paralleling task difficulty during driving. The ability of the cardiac based measures in this study to indicate changes in driver mental load despite no obvious driving performance changes substantiates claims that physiological measures give additional information about driver state, and have the potential to increase the sensitivity of studies investigating mental load in vehicles. We recommend the inclusion of HRV measures in future driving load / driver distraction research and suggest that such measures may also be used to enhance investigations into the demands placed on drivers in the real-world.

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