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## Assessing the effects of auditory-vocal distraction on driving performance and physiological measures using a driving simulator

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### ABSTRACT

In this research, a driving simulator experiment with physiological sensors is conducted to quantify the effect of an increase in workload on driving performance and physiological state in the presence of particular road situations. A secondary cognitive task with multiple levels of difficulty designed to simulate auditory-vocal distraction is added to the primary driving task. Driving performance and physiological indices such as heart rate and skin conductance level are monitored throughout the experiment. Nonparametric statistical tests are used to test the effect of the secondary task at three different road situations frequently encountered in an urban context. It is hypothesized that an increase in workload leads to variations in the driver's physiology as well as decrement in his/her driving performance. Results of the study showed that the driver adopts a regulatory behavior at the operational level (e.g., reduces the speed) in order to allow the performance of the additional task and driving at the same time. The effect of the regulatory behavior is minor on the longitudinal and lateral control measures (e.g., the speed, the pedal depression, the lane position). However, the impact on the reaction time can have important implications for road safety. An increase in the heart rate and skin conductance level reflects the increase in the cognitive workload when performing the secondary task. No major differences are found in terms of the driving performance and the physiological measures across the difficulty levels of the secondary task at the three considered road situations. In order to maintain control of driving, particularly at the high levels of difficulty, some subjects are found to pay less attention to the secondary task and shift their focus towards the primary driving task. The study highlights the advantage of implementing the driver's cognitive workload measures in the development, design, and assessment of effective in-vehicle safety systems.

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## 1. Introduction

Distraction has been identified by the National Highway Traffic Safety Administration (NHTSA) as an influential factor leading to recognition impairment while driving (NHTSA, 2008), and it is therefore considered a "risky behavior" (NHTSA, 2016). Distraction is a deviation in attention (Beratis et al., 2017), away from the primary task of driving, provoked by an

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internal or external stimulus (e.g., event, activity, object, person) causing a delay in the recognition of the information required for safe driving (Beanland, Fitzharris, Young, & Lenné, 2013; Chan & Singhal, 2013; Kaber, Liang, Zhang, Rogers, & Gangakhedkar, 2012; Stutts, Reinfurt, Staplin, Rodgman, 2001). In 2010, NHTSA addressed several variables related to distraction from internal sources and cognitive activities. Results showed that conversing with passengers was the most frequently recorded internal source of distraction. In this context, the present research focuses on auditory-vocal distraction while driving arising from cognitive workload.

Cognitive workload is directly related to the proportion of “mental capacity” spent by the human to execute a task (Brookhuis & de Waard, 2010). Considered as a latent form of distraction, workload is controlled by the context that defines the driver state. An increase in workload results in a negative type of stress known as distress. When this workload is excessive, the resulting stress is associated with road accidents (Brookhuis & de Waard, 2010). This study therefore aims at analyzing workload while driving and its impacts on driving performance with an eye towards measures that may mitigate the impacts of distraction on road safety.

### 1.1. *The driver cognitive workload*

The driver cognitive workload is defined in Brookhuis and de Waard (2010) as arising from the demand of the driving task and is classified into two types: (1) underload that contributes to impairment in both attention and alertness, and (2) overload that leads to distraction and lack in time and capacity required to process the information. Recent research work (Zhou, Yu, & Wang, 2016) studied the effect of compensatory beliefs in changing the driving behavior to self-regulate the increased demand from additional tasks at different levels. For instance, at the strategic level, the driver decides not to perform a secondary task (e.g., using a mobile phone), at the tactical level the driver regulates and adjusts the engagement time with the secondary task, and at the operational level, the driver reduces the speed when performing the secondary task.

### 1.2. *Measurement approaches*

Workload has been measured subjectively by means of self-reports (questionnaires) and by objective assessments such as driving performance and physiological measures obtained through sensors (Williamson, 2009). Miller (2001) reported that the primary task of driving can be evaluated through performance measures such as steering wheel movements (e.g., wheel reversals) and speed, while physiological measures can be classified into five areas: cardiac activity (e.g., heart rate, heart rate variability, blood pressure), respiratory activity, eye activity (e.g., eye blink rate and interval of closure), speech measures (e.g., pitch, rate), and brain activity (e.g., electroencephalogram, electrooculogram). Physiological activity naturally arises when additional workload is exerted leading to variation in physiological measures such as heart rate and skin conductance (Brookhuis & de Waard, 2011; Engström, Johansson, & Östlund, 2005; Hajek, Gaponova, Fleischer, & Krems, 2013). Mehler, Reimer, & Coughlin (2012) observe that physiological disturbances occur when the human body mobilizes resources in order to respond to the task demand and operate. Thus, monitoring physiological indices would give insight into workload magnitude (Mehler, Reimer, Coughlin, & Dusek, 2009). Under conditions of stress, anxiety, or workload increment, heart rate (in heartbeats per minute) increases, while it decreases with relaxation (Mehler, 2009; Reimer, Mehler, Pohlmeier, Coughlin, & Dusek, 2006). Also, in response to stress, the sweat gland activity and the skin conductance level (also referred to as electrodermal activity) increase (Mehler, 2009).

A number of studies have collected physiological data to measure workload in the driving context. In Healey and Picard (2005), electrocardiogram, electromyogram, skin conductance, and respiration rate measures were continuously collected during real trips conducted by subjects in the Greater Boston Area. Results showed that heart rate metrics and skin conductance were the most correlated measures with the stress level while driving. Sensitivity of physiological signals as measurements of cognitive workload was inspected in Mehler et al. (2009) in conjunction with a driving simulator experiment by introducing a secondary cognitive “n-back” task (a delayed digit recall task). Physiological data including heart rate, skin conductance, and respiration rate, in addition to driving performance measures were collected. Results showed that the three collected physiological measures can provide indications of differences in the relative workload assigned to subjects prior to, or in absence of, significant performance level decrements.

### 1.3. *Study motivations and objectives*

The aim of this research is to quantify the effect of an increase in the cognitive workload arising from a secondary auditory-vocal task with multiple levels of difficulty. It utilizes a driving simulator experiment and physiological sensors, and quantifies the effect of the secondary task on the driving performance and physiological measures (heart rate and skin conductance) at three frequently encountered road situations: sudden crossing of pedestrians, sudden truck stop, and traffic light. A particular research question of interest is to identify the regulatory behavior of the driver in response to increasing levels of difficulty of the secondary task, i.e., to what extent drivers pay attention to the secondary task versus the primary driving task. As such, this study differs from previous research work (e.g., Mehler et al. (2009) and Niezgodá, Tarnowski, Kruszewski, and Kamiński (2015)) that has investigated the effect of an increase in workload in the absence of particular road events. Studying the effects of driving distraction particularly at situations in an urban context is important as the

driving task per se in the city requires high cognitive workload. Therefore, any deviation in attention due to additional distracting activities will potentially cause risky and unsafe behavior.

The remainder of this paper consists of the following: the second section describes the adopted method. The third section presents the obtained results. The fourth section concludes the paper and discusses possible extensions of the research.

## 2. Method

This section describes the method used in this study including the apparatus, tasks, experimental design, adopted procedure, data collection, and dependent variables.

### 2.1. Apparatus

Driving simulation data are collected using the driving simulator DriveSafety DS-600c, a full-width Ford automobile cab, available at the Transportation and Infrastructure Research Laboratory of the American University of Beirut (AUB). This simulator is characterized by its high performance and fidelity and is used to assess driving behavior under controlled and customizable conditions. Driving scenarios are designed using the HyperDrive Authoring Suite that allows the user to create driving scenes from a wide library of cultures, roadways, intersections, and entities. Events are generated by means of scripted triggers (location or time based). Data are collected at the frequency of 10 Hz and are recorded in the output file of each session.

Physiological data are collected using MEDAC System/3 instrumentation unit and sensors from NeuroDyne Medical, Corp.:<sup>1</sup> the heart rate and the skin conductance data are collected using the Electrocardiogram (ECG) and the electrodermal sensors, respectively. NeuGraph software is used to collect these data (with a sampling rate of 250 Hz) and display physiological signals in real-time (NeuroDyne Medical, 2004). In order to remove movement artifacts and detect heart beats, ECG data stored in NeuGraph software are edited using ECG Wave Editor (NeuroDyne Medical, 2009). To ensure the consistency and the synchronization with the driving simulator data, edited physiological data are saved with a reduced sampling rate of 10 Hz (NeuroDyne Medical, 2009).

A recorder is placed inside the simulator to record the response of the subject in the auditory secondary task.

### 2.2. Tasks

#### 2.2.1. Driving task

The driving simulator experiment occurs in an urban context in which the subject is required to drive straight and curved roadways with one lane in each direction and parked cars on both sides. The total length of the driving course is approximately 7.5 km. Road directions are provided by means of billboards indicating the direction to be followed (e.g., “Turn Right”, “Turn Left”, and “Continue Straight”). A visual display of road directions is adopted in order to prevent interference with the auditory secondary task. If the subject does not abide by the posted directions, a dead end is reached and the experiment is terminated.

Three different road situations or events, illustrated in Fig. 1, are encountered during the driving course.

In the first situation, pedestrians cross the road suddenly in front of the driver. The start point of the segment of interest is defined as the time at which the subject reaches the location-based trigger (located 80 m before the crosswalk) which is scripted to provoke the walking movement of the pedestrians. The event ends when the subject reaches the crosswalk, which constitutes the end of the segment of interest. In the second situation, a truck initially moving ahead of the subject suddenly stops. The start point of the segment of interest is defined as the time at which the truck starts decelerating, while the end point is defined as the time at which the subject stops. In the third situation, the subject encounters a signalized intersection. Initially set to the green indication, the traffic light turns yellow, then red just before the subject reaches the intersection. The start point of the segment of interest is the time at which the traffic light turns to the yellow indication (100 m before the intersection), while the end point is defined as the time at which the traffic light turns to the red indication (30 m before the intersection). The traffic flow in the opposite direction is light except for the truck situation, where it increases to prevent the subject from overpassing the truck.

#### 2.2.2. Secondary task

The delayed digit-recall (n-back) task developed by the MIT AgeLab is adopted in this study as a secondary task assigned to the subjects in addition to the primary task of driving. This task entails three different levels of cognitive demand. In the first level (0-back), the participant is required to hold in memory one single digit number presented to him/her randomly (between 0 and 9), and to repeat it immediately after it was presented. In the second level (1-back), the subject has to recall from memory and repeat out loud the number that was presented one back prior to the current number. In the third level (2-back), the participant is required to recall from memory and to respond with the number that was presented two numbers prior to the current number (Reimer, Coughlin, & Dusek, 2009). The n-back task has been adopted in several research studies

<sup>1</sup> The company is currently managed by Tenacity Medical, Inc.



Fig. 1. The encountered driving scenarios (road situations).

such as Hajek et al., (2013); Mehler et al. (2012, 2009); Niezgodna et al. (2015); Reimer, Mehler, Wang, & Coughlin (2012); and Reimer and Mehler (2011), and has been demonstrated to be relevant for driving research in Mehler, Reimer, & Dusek (2011). Due to the cognitive resources involved in this task which are the auditory attention and the memory component, this task simulates several activities that the driver may be subjected to while driving, such as using navigation systems with auditory instructions, conversing with passengers, responding to incoming cell phone calls, etc. (Mehler et al., 2011).

### 2.3. Experimental design

The experiment includes a baseline phase, a control phase, and a treatment phase. The subject first drives a baseline phase that takes about two minutes to be completed. The baseline does not include any particular driving scenario; only traffic flow in the opposite direction is encountered. In the control phase, the subject encounters the three aforementioned road situations (pedestrians, truck, and traffic light scenarios) without being assigned the auditory n-back task. This phase lasts for five minutes. In the treatment phase, the subject encounters the three road situations while performing the n-back task at the same time. The order of presentation of the levels of the n-back task (0, 1, and 2) is randomized among subjects; however, the same sequence of numbers is presented to all subjects at each level. An interval of 2.25 s separates any two consecutive numbers being read out. Each combination of the n-back levels is scripted within one audio message. The treatment phase is initiated when the driver reaches the location-based trigger which prompts the audio message. The duration of the n-back task is five minutes in the driving course, and is independent of the driver's speed to ensure that all subjects are assigned the same workload regardless of their speed. The treatment phase is designed so that the driver encounters each of the three driving situations occurring at one particular level of the n-back task, i.e., each road event (pedestrians, truck, and traffic light) is associated with one level of the n-back task (0, 1, and 2). However, the n-back task is administered not only at the road events but throughout the entire segment that constitutes the treatment phase. The order of presentation of the three driving scenarios is also randomized among subjects in both phases (control/treatment). To summarize, a subject encounters (after driving the baseline phase) three situations twice in the overall drive: once at the control phase and another at the treatment phase. An example of the driving course design is shown in Fig. 2.

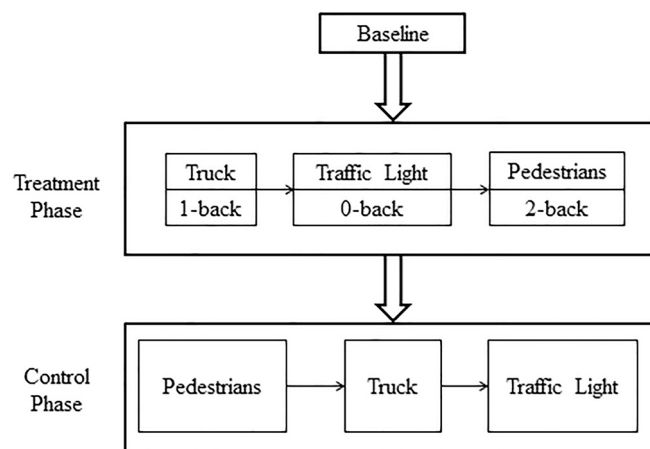


Fig. 2. Example of one possible driving course.

## 2.4. Procedure

A screening interview is conducted first to assess the subject's eligibility to participate in the experiment based on age, possession of driving license, and absence of medical conditions that may interfere with the ability to drive. Then, the subject is informed about the steps of the experiment, without being told its actual objective of assessing workload in order not to influence his/her driving behavior. After the subject signs the consent form, the research associate explains the n-back task and conducts a training session with the subject as per the training material provided in Mehler et al. (2011). After schematically showing the road to be driven in the experiment, the research associate attaches the ECG and the skin conductance sensors as per the equipment set-up documented in Mehler (2009). A practice session on the simulator then takes place to familiarize the subject with driving the simulator while the sensors are attached. The driving context in this session is similar to that of the actual experiment with no exceptional driving situations. Subjects are instructed to drive as they do in their real life, and they are informed that they are expected to abide by the traffic regulations. Subjects are also instructed to answer as accurately as they can do on the secondary task. In order to ensure that the subject is still comfortable with performing the n-back task, he/she is reminded of the n-back task by performing one additional trial with randomized levels (conducted inside the vehicle by the research associate), while the driving simulation is turned off. After a break of one minute, the actual driving experiment (around 12 min depending on the subject's speed) takes place in which the driving performance and physiological measures are collected. The subject's answers to the n-back task are also recorded. Once completed, the subject is asked to fill out a post-driving survey. This procedure was approved by the Institutional Review Board at AUB.

## 2.5. Data collection

Recruitment was based on convenience sampling of AUB students during class announcements or by randomly approaching students and inviting them to participate. A pilot test was done on three subjects before the actual start of data collection, and the experimental design was adjusted accordingly. Data collection extended from March 2017 till October 2017.

## 2.6. Dependent variables

Dependent variables of this study can be classified into driving performance and physiological measures calculated along each segment of interest at each situation in both phases. Driving performance measures are speed-related measures (average, standard deviation, and maximum), standard deviation of the lane position, accelerator pedal depression related measures (standard deviation and maximum), brake related measures (standard deviation and maximum), and the reaction time. The lane position corresponds to the lane position offset for the vehicle from the centerline of the current lane (in meters); it is positive when the offset is to the right and negative when it is to the left. The accelerator pedal depression and the brake measures are dimensionless values ranging between 0 (pedal is not being depressed) and 1 (pedal is at the maximum depression) (HyperDrive, 2006). Descriptive statistics of the measures of interest (i.e., average, standard deviation, minimum, and maximum) are computed within the segment of interest specific to each road situation. For example, the average speed at the traffic light situation is the average value of the instantaneous speed measures (collected at frequency of 10 Hz) by the driving simulator within the segment of interest of the traffic light event, and the maximum speed is the maximum of these instantaneous speed measures. The definition of the reaction time depends on the encountered situation. Since we do not use an eye tracker to detect the subject's gaze, the time at which the subject "sees" the event is assumed to be the time at which the event actually starts. For the pedestrians situation, the reaction time is defined as the time at which the pedestrians reach the driver's lane (pedestrians become visible) until the subject implements the first reaction. For the truck situation, the reaction time is defined as the time since the truck starts decelerating until the subject implements the first reaction. For the traffic light situation, the reaction time is defined as the time since the signal indication turns yellow until the subject implements the first reaction. For all situations, the first reaction is considered as braking or releasing the gas pedal. The reaction time for a red light violator is not calculated since he/she did not implement any reaction in the segment of interest. Physiological measures are heart rate and skin conductance measures (average, standard deviation, minimum, and maximum).

## 3. Results

This section includes the sample description and the statistical analysis.

### 3.1. Sample description

A total of 103 AUB students volunteered for enrollment in the study, but several of them were dropped from the analysis for a variety of reasons including: dizziness, driving in different (from instructed) directions and reaching a dead end, technical failure in the simulation or ECG sensor, overspeeding during the treatment phase and encountering more than one level of the n-back task at one particular road event, or subjects' request for withdrawal. The remaining sample consists of

80 students: 53 males and 27 females. Thirty-five students were considered inexperienced drivers who have been driving for less than two years, and forty-five students were considered experienced drivers who have been driving for more than two years. Thirty-seven subjects encountered the control phase before the treatment phase and forty-three subjects encountered the treatment phase before the control phase.

### 3.2. Statistical analysis

In order to test the normality of data, Shapiro test was used. Several data vectors were not normal at the 95% level of confidence ( $p < 0.05$ ), such as the average speed ( $p = 0.006$ ) and the maximum heart rate ( $p = 0.033$ ) at the 0-back level for the pedestrians situation. Therefore, nonparametric tests are used for analysis.

Paired (within-subject) analysis between the control and treatment phases is conducted to test the effect of the secondary task. Then, dependent variables of interest are compared between levels of the n-back task for a given road situation. In the following, each road situation is considered separately.

#### 3.2.1. Effect of the n-back task

In this section the effect of the n-back task on driving performance and physiological measures is investigated using paired comparison, within each subject, to test for differences between the control and treatment phases using Wilcoxon Signed-Ranks test.<sup>2</sup> Descriptive statistics of each dependent variable of interest (median and interquartile range or IQR<sup>3</sup>) along with the resulting p-values are presented in Table 1 for the driving performance measures and Table 2 for the physiological measures.

As shown in Table 1, there are statistically significant differences at the 95% level of confidence in the maximum speed ( $p = 0.022$ ), the standard deviation of pedal depression and the maximum pedal depression ( $p = 0.008$  and  $p = 0.004$ , respectively) between the control and treatment phases at the pedestrians situation with higher median values in the control phase. A statistically significant difference in the standard deviation of the lane position ( $p = 0.001$ ) is found at the truck situation with higher median value in the control phase. Statistically significant differences in the average and maximum speed ( $p = 0.007$  and  $p = 0.006$ , respectively), maximum pedal depression ( $p = 0.005$ ), standard deviation of brake and maximum brake ( $p = 0.012$ ) are found at the traffic light situation, with higher median values in the control phase. Additional statistically significant differences are observed at the 90% level of confidence between the control and treatment phases in terms of the standard deviation of brake (pedestrians situation), maximum speed (truck situation), and standard deviation of the pedal depression (traffic light situation).

While an anticipated effect of the n-back task would be to increase variability as indication of driving performance decrement, results have shown a decrease in the standard deviation of the lane position, pedal depression, and brake at the treatment phase. Results also showed a decreasing trend in the average and maximum speed, maximum pedal depression and maximum brake in the treatment phase. This occurs because additional cognitive resources (i.e., auditory attention and memory) are utilized in response to the increase in workload while driving and performing the secondary task at the same time (treatment phase). For example, within the segment of interest at the traffic light event, the median average speed decreases at the treatment phase by approximately 1.3 km/hr. Such modest decrease in the average speed should not be seen as improvement in the driving performance. This could be explained by the compensatory effort of the driver who adopts a regulatory behavior that rectifies the effect of the distracted task by an additional control over the driving task. Mehler et al. (2009) discussed the driver's compensatory response and found that the variability of the lateral control decreases when cognitive workload increases.

Zhou et al. (2016) studied the contribution of compensatory beliefs with respect to the usage of the mobile phone while driving, manifested by statements such as "I can use a mobile phone now because I will slow down". They showed that drivers with higher propensity to compensatory beliefs were more involved in road accidents as a result of the usage of a mobile phone while driving at the same time. Clarkson, Hirt, Jia, and Alexander (2010) reported that resources will deplete after excessive self-regulatory efforts on successive tasks, and subsequently, any attempt of self-regulation will fail.

To summarize, the regulatory behavior is manifested by minor variations in the longitudinal and lateral control measures (e.g., speed, lane position) between the treatment and the control phases. However, resources available to keep control of the driving task might deplete over time causing an impairment in the driving performance, as evidenced by the literature. Therefore, the self-regulatory behavior in response to distracting tasks is a risky behavior that endangers driving safety.

As shown in Table 2, statistically significant differences are observed, at the 95% level of confidence, between the control and treatment phases in the average, minimum and maximum heart rate and skin conductance level values at the three situations ( $p < 0.05$ ), with higher median values observed in the treatment phase, demonstrating a higher workload, and a higher level of stress, due to the n-back task. Fig. 3 represents a boxplot of the average heart rate at the pedestrians event. As shown in this figure, the average heart rate at the treatment phase increased by approximately 7 beats/min. These results are in accordance with the findings of Mehler et al. (2012, 2009) that state that the driver exhibits an increase in the heart rate and skin conductance as a result of the body's activation of resources to perform additional cognitive tasks.

<sup>2</sup> Wilcoxon Signed-Ranks test is a nonparametric test used when observations are paired and have not met the normality assumption. It is analog to the paired two-sample t-test and tests the median difference between the pairs of each dependent variable of interest.

<sup>3</sup> IQR of each data vector is presented as 1st quartile-3rd quartile.

**Table 1**  
Driving performance measures (comparing control/treatment phases).

Situation	Phase	Descriptive statistics	Speed (km/hr)			Lane position (m)	Pedal depression (dimensionless)		Brake (dimensionless)		Reaction time (s)
			Av.	S.D.	Max.	S.D.	S.D.	Max.	S.D.	Max.	
Pedestrians	Control	Median	32.85	15.47	51.39	0.08	0.16	0.45	0.13	0.38	0.50
		IQR	30.56–35.87	11.33–18.00	50.01–53.81	0.05–0.11	0.12–0.21	0.36–0.53	0.09–0.17	0.27–0.53	0.20–0.80
	Treatment	Median	32.54	14.02	50.55	0.08	0.15	0.41	0.12	0.37	0.50
		IQR	30.18–35.12	10.39–18.21	46.15–53.46	0.06–0.11	0.12–0.19	0.33–0.50	0.07–0.18	0.20–0.52	0.30–0.83
	p-value	0.891	0.170	0.022**	0.808	0.008**	0.004**	0.090*	0.117	0.330	
Truck	Control	Median	21.31	17.49	47.89	0.06	0.11	0.33	0.06	0.21	3.20
		IQR	18.42–24.39	15.07–19.75	43.57–52.37	0.04–0.09	0.07–0.15	0.25–0.43	0.04–0.09	0.13–0.31	1.93–4.68
	Treatment	Median	21.29	17.47	46.80	0.05	0.10	0.31	0.06	0.19	3.50
		IQR	17.99–23.02	15.12–19.34	42.12–50.65	0.03–0.07	0.08–0.13	0.26–0.39	0.03–0.10	0.12–0.29	2.73–4.58
	p-value	0.340	0.521	0.068*	0.001**	0.121	0.128	0.478	0.692	0.178	
Traffic Light	Control	Median	46.22	1.85	49.31	0.06	0.09	0.39	0.00	0.00	5.80
		IQR	42.66–49.20	1.29–2.86	45.40–52.26	0.05–0.10	0.04–0.16	0.29–0.50	0.00–0.00	0.00–0.02	4.50–6.60
	Treatment	Median	44.90	1.70	47.53	0.05	0.09	0.39	0.00	0.00	6.10
		IQR	41.38–47.85	1.09–2.17	43.43–50.84	0.04–0.08	0.03–0.15	0.27–0.45	0.00–0.00	0.00–0.00	5.20–6.60
	p-value	0.007**	0.187	0.006**	0.109	0.094*	0.005**	0.012**	0.012**	0.164	

\* Significance at the 90% level of confidence.

\*\* Significance at the 95% level of confidence.

**Table 2**  
Physiological measures (comparing control/treatment phases).

Situation	Phase	Descriptive statistics	Heart rate (beats/min)				Skin conductance level (micromhos)			
			Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.
Pedestrians	Control	Median	77.25	4.04	71.09	85.23	15.70	0.21	15.44	16.52
		IQR	69.47–88.01	2.67–5.83	64.66–78.95	79.37–96.77	11.24–21.89	0.10–0.47	10.84–21.68	11.59–22.86
	Treatment	Median	84.10	3.98	78.13	92.59	16.26	0.21	15.99	17.16
		IQR	73.48–90.45	2.56–5.14	67.26–85.71	83.33–100.00	13.02–22.47	0.11–0.41	12.24–21.98	13.4–22.94
	p-value		0.000**	0.289	0.000*	0.000**	0.000**	0.611	0.000**	0.009**
Truck	Control	Median	75.83	3.60	68.50	84.99	16.00	0.12	15.83	16.43
		IQR	69.79–84.55	2.63–5.19	62.57–79.37	76.44–93.17	11.36–21.81	0.07–0.31	11.21–21.22	11.75–22.15
	Treatment	Median	81.85	4.01	73.00	91.74	16.93	0.16	16.54	17.31
		IQR	73.68–90.85	2.89–5.87	66.37–83.68	84.04–100.67	12.16–22.09	0.10–0.37	11.78–21.68	12.73–22.80
	p-value		0.000**	0.101	0.000**	0.000**	0.245	0.000**	0.000**	0.000**
Traffic light	Control	Median	78.59	2.81	73.53	85.23	16.11	0.09	15.91	16.24
		IQR	70.04–90.13	2.05–4.01	65.08–84.99	75.19–95.24	11.64–21.81	0.05–0.19	11.42–21.48	11.75–22.00
	Treatment	Median	89.61	2.71	81.97	94.34	16.74	0.10	16.65	17.10
		IQR	79.53–98.50	1.83–4.09	73.71–93.46	85.13–102.04	12.87–23.00	0.07–0.18	12.70–22.68	13.00–23.29
	p-value		0.000**	0.734	0.000**	0.000**	0.000**	0.646	0.000**	0.000**

\*\* Significance at the 95% level of confidence.

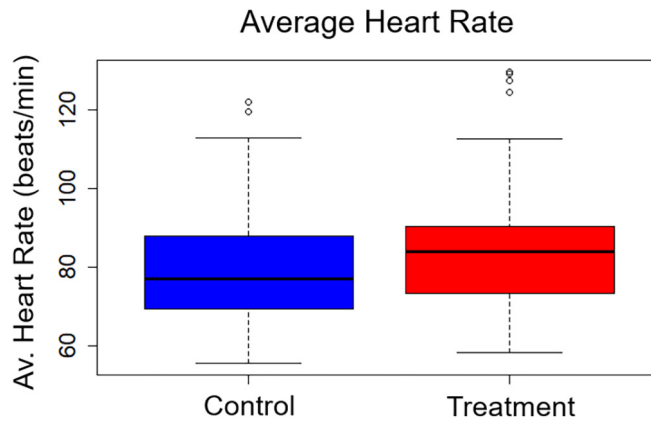


Fig. 3. Boxplot of the average heart rate at the pedestrians event.

### 3.2.2. Effect of the order of presentation of the treatment phase

We further investigate the effect of the order of presentation of the treatment phase (i.e., whether it occurred before or after the control phase) on the variables of interest. A mixed design analysis was done including the effect of the encountered phase as a within-subject variable with two levels (control or treatment), the effect of the order of presentation of the treatment phase in the driving course as a between-subjects variable with two levels (before or after the control phase), and the interaction between the two variables. The analysis showed that there is only an effect of the encountered phase variable on the variation of the physiological measures between the treatment and the control phases. However, the interaction between the two factors (the encountered phase and the order of presentation of the treatment phase) is found to affect the reaction time, i.e., the effect of the encountered phase (whether it is a control or treatment) on the reaction time depends on the order of presentation of the treatment phase in the driving course (whether it is encountered before or after the control phase).

To further investigate the effect of the order of presentation of the treatment phase in the driving course, subjects were classified into two groups according to the order of presentation of the treatment phase. Paired within-subject comparisons were then conducted on each group separately with respect to driving performance measures.

For the case where subjects encountered the treatment phase before the control phase, there was a statistically significant difference between the control and treatment phases, at the 95% level of confidence, in the reaction time at the pedestrians and the traffic light situations ( $p = 0.001$  and  $p = 0.037$ , respectively) with a higher reaction time occurring in the treatment phase, an expected distraction outcome of the n-back task. Similar results were reported in Reimer, Mehler, Reagan, Kidd, & Dobres (2016) where engaging in cell phone conversations while driving increased the reaction time.

For the case where subjects encountered the control phase before the treatment phase, statistically significant difference (95% level of confidence) at the pedestrians situation is found in the reaction time ( $p = 0.026$ ) with higher median value in the control phase.

The difference in the direction of variation observed in the reaction time between the two cases could be attributed to the effect of learning and expectation that might have influenced the driver's reaction time when the same road situation is encountered twice.

Fig. 4 shows a boxplot of the reaction time at the traffic light event for the case whereby the treatment phase is encountered before the control phase. The reaction time increased at the treatment phase by approximately 1 s due to the secondary task. Such increase in the reaction time is reported in Lee et al. (2001) to have important implications for the driver safety and thus demonstrates that being engaged in secondary cognitive tasks while driving is a risky behavior.

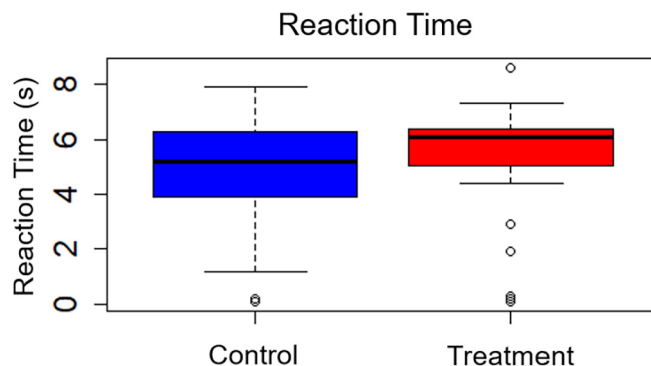


Fig. 4. Boxplot of the reaction time at the traffic light event.

### 3.2.3. Differences between levels of the n-back task

A comparison between the levels of the n-back task (0, 1, and 2) is conducted for each road situation using Kruskal-Wallis H test.<sup>4</sup> For example, data extracted from subjects who encountered the truck situation at the 0-back level are compared to data extracted from subjects who encountered the truck situation at the 1-back level, and to data extracted from subjects who encountered the truck situation at the 2-back level. Results for all situations with respect to driving performance measures are presented in Table 3, and with respect to physiological measures in Table 4.<sup>5</sup>

As shown in Table 3, there are no statistically significant differences in the driving performance measures at the 95% confidence level between the three levels of the n-back task at all situations. These results are in line with the findings of Niezgodá et al. (2015) where driving performance measures such as the lateral and longitudinal control of the vehicle and the mean and standard deviation of the speed were not affected by the difficulty level of the n-back task. They are also in line with the findings of Mehler et al. (2009) where the effect of the n-back task level on the driving performance measures was reported as “modest”. Moreover, since the effect of the levels of the n-back task is assessed in this study at three particular road situations, the non-existence of statistically significant differences in the driving performance measures can also imply that the encountered situation dominates the secondary task, and the driving behavior is dictated by the situation itself regardless of the level of the secondary task; thus, drivers respond to the driving task needs and react relatively in a similar manner in order to fulfill the safety requirements of the driving task (e.g., reducing the speed, braking, etc.).

As shown in Table 4, there are no statistically significant differences, at the 95% level of confidence, in the physiological measures across the three levels of the n-back task at the traffic light situation. Statistically significant differences at the 95% level of confidence in the average ( $p = 0.023$ ), minimum ( $p = 0.009$ ) and maximum ( $p = 0.035$ ) heart rate are found at the truck situation. Multiple comparisons (with Bonferroni adjustment) showed statistically significant differences at the 95% level of confidence between the 0-back and 2-back levels in the average ( $p = 0.022$ ), minimum ( $p = 0.006$ ), and maximum ( $p = 0.040$ ) heart rate with higher median values at the 2-back level. Statistically significant differences at the 90% level of confidence are observed at the pedestrians situation in terms of the average heart rate ( $p = 0.065$ ), minimum heart rate ( $p = 0.054$ ), and the standard deviation of the skin conductance level ( $p = 0.097$ ). Multiple comparisons (with Bonferroni adjustment) only showed statistically significant differences at the 90% level of confidence between the 0-back and 2-back levels in the average ( $p = 0.088$ ) and minimum ( $p = 0.070$ ) heart rate with higher median values observed at the 2-back level. Although variation in physiological indices is expected to reflect variation in the workload level, particularly in the n-back task, the results of this study did not show a prevailing effect of the task difficulty levels on the physiological measures, unlike the findings of previous studies. This may be because previous studies, such as Mehler et al. (2009) used a period of analysis of two minutes for each level of the n-back task with no variation in the driving environment (a 2-minute period of analysis is justified in Mehler et al. (2011) as a wide duration enough to reveal variations in physiological metrics), while this research studied the effect of the secondary task at a particular instantaneous event, with a shorter duration of time (<10 s), which may not necessarily lead to significant variations in the physiological measures with respect to the levels of the secondary task.

As for the performance on the secondary task, Kruskal-Wallis H test showed a statistically significant difference between the levels of the n-back task in terms of the number of errors occurring at each level ( $p = 0.000$ ). Nineteen percent of the total errors occurred at the 0-back level, 20% at the 1-back level, and 61% at the 2-back level, implying a decrement in the overall performance on the n-back task as the cognitive workload increases.

Further investigation is conducted to compare the driving performance of the subjects who perfectly performed the n-back task with its three levels of difficulty (i.e., they did not commit errors when performing the n-back task) and the subjects who at least committed one error when performing the n-back task. This analysis is motivated by the fact that drivers in real life might completely pay attention to the secondary task (those are represented in the experiment by the group of subjects who perfectly performed the n-back task) or ignore/pay less attention to it at some level of difficulty (those are represented by the group of subjects who at least committed one error in the n-back level). Table 5 shows a breakdown of the subjects according to their performance on the secondary task at each level.

For this comparison, the Mann-Whitney U-Test<sup>6</sup> is used. Results showed that driving performance measures at the three road situations did not statistically significantly differ at the 95% level of confidence between subjects who perfectly performed the n-back task and those who at least committed one error when performing the secondary task. This implies that subjects had relatively similar driving performance (i.e., average speed, standard deviation of lane position, maximum accelerator pedal depression, reaction time) regardless of whether they performed the n-back task completely correctly or not. Thus, we conclude that drivers were behaving in such a way that they remain attentive to the primary driving task as if they were prioritizing it. Nevertheless, some subjects had to pay less attention to the secondary task (they responded incorrectly to the n-back task as a result), particularly at the high levels of difficulty, in order to retain control of driving when performing the secondary task at the same time. On the other hand, others were able to maintain their driving performance and perfectly perform the n-back task. Subjects seemed to distribute the effort or energy so that the main driving task does not suffer differently as a result of

<sup>4</sup> The Kruskal-Wallis H test is a nonparametric test that is analog to the one-way ANOVA. It is used to determine whether three or more independent samples were selected from populations having the same distribution.

<sup>5</sup> Difference-in-differences measures (to net out any differences arising due to different driving behavior or physiological measures in the control phase) were also computed across the three samples and have led to similar conclusions.

<sup>6</sup> The Mann-Whitney U-Test is a nonparametric statistical test analog to the two-sample *t*-test. It is also known as the Wilcoxon Rank Sum test.

**Table 3**  
Driving performance measures (comparing the n-back levels).

Situation	n-Back level	Descriptive statistics	Speed (km/hr)			Lane position (m)	Pedal depression (Dimensionless)		Brake dimensionless		Reaction time (s)
			Av.	S.D.	Max.	S.D.	S.D.	Max.	S.D.	Max.	
Pedestrians	0	Median	33.13	15.22	51.19	0.08	0.15	0.42	0.12	0.37	0.30
		IQR	31.49–35.12	10.39–17.36	47.99–53.70	0.06–0.10	0.12–0.19	0.34–0.51	0.06–0.16	0.19–0.50	0.20–0.80
	1	Median	33.35	12.23	52.72	0.08	0.16	0.44	0.13	0.36	0.50
		IQR	30.38–38.83	7.3–18.52	46.77–53.55	0.06–0.09	0.13–0.21	0.36–0.50	0.07–0.16	0.22–0.47	0.23–0.68
	2	Median	32.07	15.52	50.55	0.08	0.14	0.36	0.14	0.40	0.50
		IQR	29.41–33.72	12.07–18.92	46.04–52.99	0.06–0.11	0.12–0.16	0.32–0.46	0.09–0.19	0.26–0.55	0.28–0.90
p-value		0.468	0.348	0.920	0.977	0.306	0.337	0.632	0.798	0.618	
Truck	0	Median	20.71	17.77	47.20	0.05	0.09	0.31	0.07	0.22	3.10
		IQR	17.83–22.93	16.34–19.25	44.10–51.30	0.04–0.07	0.08–0.11	0.27–0.35	0.04–0.11	0.12–0.38	2.40–4.10
	1	Median	21.59	17.50	47.99	0.06	0.10	0.30	0.06	0.18	3.85
		IQR	18.28–23.20	15.81–19.37	41.94–50.69	0.03–0.08	0.08–0.13	0.26–0.41	0.04–0.09	0.13–0.27	2.40–4.75
	2	Median	21.05	17.43	45.42	0.05	0.10	0.35	0.05	0.17	3.55
		IQR	18.36–23.67	14.44–19.81	42.52–49.86	0.03–0.06	0.08–0.14	0.25–0.42	0.03–0.08	0.10–0.26	2.93–4.18
p-value		0.852	0.817	0.760	0.867	0.374	0.726	0.285	0.448	0.518	
Traffic light	0	Median	45.20	1.81	48.19	0.06	0.11	0.39	0.00	0.00	6.20
		IQR	41.57–48.68	1.27–2.19	43.58–51.31	0.03–0.08	0.03–0.15	0.29–0.43	0.00–0.00	0.00–0.00	5.43–6.73
	1	Median	44.49	1.30	47.05	0.05	0.09	0.37	0.00	0.00	5.65
		IQR	41.39–47.36	1.02–1.89	43.16–49.45	0.03–0.08	0.03–0.14	0.27–0.46	0.00–0.00	0.00–0.00	5.20–6.05
	2	Median	44.90	1.78	49.48	0.05	0.10	0.39	0.00	0.00	6.35
		IQR	41.57–48.60	1.13–3.11	45.56–51.12	0.04–0.07	0.05–0.14	0.29–0.49	0.00–0.00	0.00–0.01	4.50–7.25
p-value		0.732	0.156	0.308	0.730	0.689	0.743	0.449	0.615	0.197	

**Table 4**  
Physiological measures (comparing the n-back levels).

Situation	n-Back level	Descriptive statistics	Heart rate (beats/min)				Skin conductance level (micromhos)			
			Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.
Pedestrians	0	Median	78.34	3.99	71.09	84.75	16.10	0.21	15.79	16.94
		IQR	69.17–89.44	2.67–4.57	65.79–82.42	76.14–100.00	13.02–21.28	0.15–0.40	12.82–20.14	13.42–22.34
	1	Median	83.49	3.83	77.93	90.10	16.26	0.16	16.10	16.88
		IQR	76.31–89.95	2.70–5.39	69.61–83.45	85.12–97.72	10.36–21.95	0.06–0.36	10.19–21.45	10.43–23.75
	2	Median	89.21	3.85	81.97	98.68	18.08	0.35	17.11	19.23
p-value	IQR	83.55–99.04	2.38–4.74	77.93–91.75	88.76–107.14	14.12–22.74	0.14–0.68	13.27–22.03	14.89–23.46	
Truck	0	Median	79.22	4.28	70.09	86.71	16.55	0.16	16.42	16.83
		IQR	73.49–84.63	3.26–6.04	60.98–79.37	81.97–93.17	12.15–21.50	0.11–0.37	11.74–21.08	13.20–21.90
	1	Median	81.65	4.20	72.12	93.46	16.55	0.14	16.02	16.79
		IQR	75.01–92.76	2.82–5.78	66.46–85.71	81.60–102.06	12.08–22.23	0.09–0.25	11.86–21.89	12.35–22.57
	2	Median	89.57	3.50	81.54	96.46	17.43	0.21	17.02	18.86
p-value	IQR	76.54–98.66	2.71–5.67	71.35–93.40	85.24–104.94	12.57–23.56	0.11–0.41	12.19–23.04	13.20–23.87	
Traffic light	0	Median	91.80	3.32	86.72	97.41	17.34	0.10	17.11	17.71
		IQR	82.90–96.99	2.14–4.21	77.72–93.61	88.76–101.35	12.10–23.66	0.05–0.18	12.01–23.47	12.18–23.83
	1	Median	87.98	2.50	81.09	92.59	16.86	0.14	16.73	17.11
		IQR	75.25–101.08	2.03–4.04	70.36–95.88	77.52–106.40	14.53–20.89	0.09–0.18	14.15–20.52	14.69–21.06
	2	Median	84.57	2.16	78.95	92.02	16.71	0.09	16.65	16.84
p-value	IQR	80.61–93.58	1.58–4.09	75.00–89.56	85.96–97.47	12.12–21.59	0.08–0.18	12.01–21.36	12.24–21.85	

\* Significance at the 90% level of confidence.

\*\* Significance at the 95% level of confidence.

**Table 5**

Breakdown of the subjects according to their performance on the secondary task at each level.

Secondary task performance	0-back	1-back	2-back
Subjects who perfectly performed the n-back level of the secondary task (0 errors)	72	52	39
Subjects who at least committed one error in the n-back level	8	28	41

performing additional tasks. For some subjects, executing more effort to keep control of the primary driving task and investing less resources on the secondary task lead to an impairment of the latter.

#### 4. Conclusion

This research studied the effect of a secondary cognitive task (n-back task) with multiple levels of difficulty on the driving behavior and physiological measures for different road situations: the driver encountering pedestrians, the vehicle ahead stopping suddenly, and a traffic light turning from yellow to red as the driver approaches. A driving simulator experiment was designed with baseline, control, and treatment phases. Subjects encountered each road situation twice in the drive, once with the n-back task being assigned and another without the n-back task. The order of presentation of this task was randomly assigned among subjects. Driving performance measures including speed, lane position, pedal depression, brake, and reaction time, in addition to physiological measures, such as heart rate and skin conductance level were analyzed at each of the road situations.

The decreased pattern of the driving performance measures (e.g., average and maximum speed, maximum pedal depression and brake) within each subject from the control phase to the treatment phase demonstrated the regulatory behavior adopted by the driver in response to the increase in the cognitive workload arising from the secondary task at the treatment phase. Moreover, the decrease in variability at the treatment phase, manifested by the decrease in the standard deviation of the lane position and the pedal depression, demonstrated the compensatory effort of the driver at the operational level to maintain control over the driving task when engaged in unsafe behavior such as performing distracting tasks. Though self-regulatory behavior appeared as such to ameliorate the driving performance to some minor extent, its effect on driving safety was limited as evidenced by the longer time taken to implement a reaction in response to a sudden road event encountered for the first time at the treatment phase compared to the control phase. Therefore, self-regulatory behavior, in response to competing activities, should be cautiously perceived when addressing driving safety. The impact of the n-back task on physiological measures was substantive. Both heart rate and skin conductance level increased with the additional workload of the secondary task. As for the levels of difficulty of the n-back task, results did not show strong evidence of variations with respect to the driving performance and physiological measures across all levels. Exerting additional effort to keep control of the main driving task when performing the secondary task caused the shift in attention from the latter to the former; for some subjects paying less attention to the secondary task was reflected in deterioration in its performance.

The findings of this study contribute to a better understanding of the impacts of auditory-vocal distraction at frequently encountered road situations in urban settings with implications for road safety. Physiological measures, such as heart rate and skin conductance level, can be used as objective tools to dynamically monitor the evolution of the driver's cognitive workload in real time when engaged with auditory-vocal tasks. This is particularly of advantage with the in-vehicle increased level of automation that complicates the human-machine interface (HMI) and introduces additional cognitive and attentional demands. In this regard, the implementation of physiological indices in the development of new technologies can help optimize the design of safety systems that aim at alerting the driver to potential risks, notably at road events. Moreover, measures of the driver's cognitive workload, including physiological indices and driving performance measures, could be used to evaluate and rate the effectiveness of available/new safety systems.

The study has a number of limitations and may be extended in future research. Using a driving simulator experiment might not exactly replicate real life driving conditions. The simulator used nonetheless is a mid-level simulator with relative validity. The findings are specific only to the population of young students and may be extended in the future to include other demographic segments and larger samples. Moreover, self-selection bias might have been introduced if the driving behavior of those who volunteered to participate in the study is different from that of non-participants.

The next steps of this research include investigating the effect of the secondary task not just at the road situation itself but after the situation ends to see if the effect of distraction carries over the driving course. Subjective workload and stress measures from the post-driving survey may also be correlated with the results derived from the driving simulator and the physiological sensors to account for the subjects' propensity to stress and distraction. Finally, econometric models are currently being developed by the authors (Tarabay, 2018) to predict the driving behavior under the encountered road situations and workload levels.

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