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The effects of driving environment complexity and dual tasking on drivers' mental workload and eye blink behavior

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ABSTRACT

The goal of the present study was to assess the effectiveness of eye blink behavior in measuring drivers' mental workload. Previous research has shown that when mental workload increases with the primary task difficulty, blink frequency drops. On the opposite, the number of blinks increases when a cognitive secondary task has to be performed concurrently. However, the combined effects of the primary task difficulty and dual-tasking on blink rate have not been investigated. The present study was thus designed to vary systematically both the primary driving task and the cognitive secondary task demand to examine their combined effects on blink rate. The driving task was manipulated by varying the complexity of a simulated driving environment. The cognitive load was manipulated using a concurrent simple reaction time task or a complex calculation task. The results confirmed that eye blink frequency was a sensitive measure to elicit increased mental workload level coming from the driving environment. They also confirmed that blink rate increased with the introduction of a cognitive secondary task while blink duration was not affected. However, eye blink behavior did not provide a clear mental workload signature when driving task demands and dual-task conditions were varied simultaneously. The overall picture goes against the suitability of eye blink behavior to monitor drivers' states at least when external and internal demands interact.

1. Introduction

Driving a vehicle imposes perceiving, identifying and anticipating road elements and other road users' behavior while maintaining an appropriate control of steering and speed. Drivers have then to pay and shift attention to multiple task-relevant objects and to process a large amount of visual and spatial information in a highly dynamic situation. However, allocation of attention and information processing may be impaired by mental workload level (Brookhuis & de Waard, 2010), which could lead to errors or degraded control of the vehicle. For example, data from the naturalistic 100-car study showed that lapses of attention were the first contributing factor to crashes (Dingus et al., 2006; Klauer, Dingus, Neale, Sudweeks, &

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Ramsey, 2006). This study noted that 78% of accidents and 65% of near crashes were associated with driver inattention, with the majority due to secondary task.

Mental workload refers to "the portion of operator information processing capacity or resources that is actually required to meet system demands" (Eggemeier, Wilson, Kramer, & Damos, 1991, p. 207). Mental workload can thus be seen as the result of the interaction between task demands and the attentional resources capacity of the operator (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014; O'Donnell & Eggemeier, 1986; Recarte, Pérez, Conchillo, & Nunes, 2008; Teh, Jamson, Carsten, & Jamson, 2014). Operator's capability depends on intrinsic factors such as age and experience and temporary states due to drowsiness or drug consumption (e.g., Cantin, Lavallière, Simoneau, & Teasdale, 2009; Cuenen et al., 2015; Patten, Kircher, Östlund, Nilsson, & Svenson, 2006). Task demand is also multifaceted. It can be categorized between external demands (i.e., coming from the road environment) and demands coming from inside the vehicle (i.e., phoning or interacting with driving assistance or in-vehicle information systems).

Following Patten, Kircher, Östlund, and Nilsson (2004), Patten et al. (2006), external demand of the driving task depends on the level of requirements placed upon information processing and/or vehicle handling. Traffic density (e.g., Brookhuis, de Vries, & de Waard, 1991; Hao et al., 2007; Teh et al., 2014) and type of maneuver (e.g., Cantin et al., 2009; Hancock, Wulf, Thom, & Fassnacht, 1990) are factors that act upon both information processing and vehicle handling and have been highlighted as affecting the level of drivers' mental workload. Complexity of the driving environment, on which the present study is focused, also affects drivers' mental workload.

Some studies dealing with the effects of driving environment complexity on task demands have used a peripheral detection task (PDT) as a secondary subsidiary task requiring simple manual responses to visual stimuli, to measure drivers' mental workload level. Törnros and Bolling (2006) examined the effects of rural and urban environments of varying speeds and complexities on drivers' workload. Results showed that urban driving tapped more on attentional resources than rural driving as reaction times to the secondary subsidiary task were longer in the former environment. Similar results were found by Patten et al. (2006) who examined in a field study the effects of route complexity. Depending on the demands placed upon information processing and/or vehicle handling, route was classified as being of high (e.g., driving in city centre environments), medium (e.g., negotiating regulated intersections) or low complexity (e.g., driving freely in urban, rural or motorway environments). Results revealed an upward trend in the reaction times to the subsidiary task with increasing route complexity (for similar effects of the complexity of the driving environment on drivers' mental workload, see Ariën et al., 2013; Jahn, Oehme, Krems, & Gelau, 2005, or Verwey, 2000).

Young et al. (2009) examined the effects of road type (i.e., urban, rural and motorway environments) on driving performance, subjective workload measure and visual behavior. Road type was shown to affect the number of lane excursions and the time spent out of the lane but not self-rated scores of mental workload. Compared to the urban condition which was used as an arbitrary reference, lateral control was more stable in the motorway condition but it was degraded in the rural environment. In addition, fewer fixations were directed outside the road in the rural driving environment when compared to the motorway and urban driving environments, suggesting increased task demands in the former environment. Similar visual behavior was found by Victor, Harbluk, and Engström (2005), as driving rural curved roads exhibited higher proportion of fixations on the road centre than rural straight roads or motorway. In a car following situation, Jamson and Merat (2005) examined the effects of varying the driving task demands on longitudinal and lateral control of the vehicle by comparing straight and curved sections of road. When driving on a winding road section, mean speed was slower, lane position was more variable and the number of steering wheel corrections increased, which suggest a higher level of drivers' workload. On the opposite, de Waard, Jessurun, Steyvers, Raggatt, and Brookhuis (1995) compared two different roadside environments (curved road in woodland area vs. straight road in moorland area) but no significant effects on driving performance or physiological mental load measures were found.

Previous research dealing with the effects of driving environment on mental workload and driving behavior has shown contrasting results regarding the effects of rural and urban driving environment. This could come from the large variety in the complexity of driving environments. It could otherwise come from the large range of mental workload measures that have been used.

Although convergence between different mental workload measures has been shown on some occasions (e.g., Benedetto et al., 2014; Recarte et al., 2008), performance and subjective measures are not always reliable indexes of workload (e.g., Yeh & Wickens, 1988; see also Hao et al., 2007; Young et al., 2009). Measuring drivers' workload objectively and reliably is an important issue for the monitoring of drivers' attentional states (e.g., Tsai et al., 2007) or the evaluation of in-vehicle users interfaces (e.g., Solovey, Zec, Garcia Perez, Reimer, & Mehler, 2014). Among the physiological measures available, several indices have been shown to be sensitive to mental workload variations. O'Donnell and Eggemeier (1986) reported that the most frequently used variables are heart rate (e.g., Di Domenico & Nussbaum, 2011), EEG signals (e.g., Baldwin & Coyne, 2003; Borghini et al., 2014; Savage, Potter, & Tatler, 2013) and eye activity measures (e.g., Konstantopoulos, Chapman, & Crundall, 2010; Lehtonen, Lappi, & Summala, 2012). Of all the eye-related measures, eye blinking has the potential to provide a useful and reliable signature of drivers' mental workload variations (Savage et al., 2013). Such potential is based on the unobtrusive nature of this measure as eye blinks are not guided by top-down or bottom-up scene exploration processes, as is the case with fixations (e.g., Tatler, Hayhoe, Land, & Ballard, 2011), nor are they affected by light conditions, as is the case when measuring pupil diameter (e.g., Pedrotti et al., 2014). In addition, they do not interfere with the primary driving task. However, previous research showed that mental workload increase has contrasting effects on blink frequency depending on whether it comes from the primary task difficulty or from the presence of a concurrent secondary task.

In a lane-change task, Benedetto et al. (2014) compared two motorcycle simulator configurations (a static and a dynamic one) which were supposed to impact vehicle handling through the assessment of the underlying mental workload. They showed that the dynamic configuration triggered a higher mental workload level, as revealed by performance and subjective workload measures, and that the number of blinks was lower in the dynamic than in the static simulator configuration. Hancock et al. (1990) compared eye blink frequency and performance to a PDT while the difficulty of driving maneuvers was varied. Maneuvers could be of low (driving on a straight road section), medium (turning right with no oncoming traffic) or high difficulty (turning left with oncoming traffic). Results confirmed that mental workload increased with driving maneuver difficulty as reaction times to the visual stimulus were significantly longer for left and right-turns than straight-lane driving. Results also showed that blink rate was lower for left and right turns than for straight portions of road. Similar downward trend in the eye blink rate with increased primary task difficulty has also been shown in cognitive or visuo-spatial tasks (e.g., Holland & Tarlow, 1972; Van Orden, Limbert, Makeig, & Jung, 2001). According to Bauer, Strock, Goldstein, Stern, and Walrath (1985), the suppression of blinks as task demands increase reflects the greater attention paid by participants to task-relevant stimuli. According to Veltman and Gaillard (1996), the number and duration of blinks decreases because more information has to be processed. Blink inhibition can, therefore, be seen as a mechanism to cope with increased task demands by reducing the risk of missing incoming information (Fogarty & Stern, 1989; Recarte et al., 2008; Stern, 1980).

However, different patterns of results have been shown when mental workload level increases due to the introduction of a concurrent secondary task. Tsai, Viirre, Strychacz, Chase, and Jung (2007) and Benedetto et al. (2014) showed that blink frequency increased during a dual driving and mental arithmetic task as compared with a driving-only task. Similarly, Savage et al. (2013) showed that more blinks were made when a problem-solving task was added to a hazard perception test. Recarte et al. (2008) compared blink frequency in a visual search task alone and in several dual-task conditions (a visual search while listening, talking or calculating). The results revealed that cognitive secondary tasks led to an increase in blink frequency, with significant increments between the listening task and the two other secondary tasks. In contrast, Benedetto et al. (2011) did not reveal significant differences between a single driving task and a dual driving and visual search task on blink frequency. Yet, using a more detailed analysis of blink duration, the authors showed that short blinks (70–100 ms) were significantly more frequent in the dual-task condition as compared with driving-only task, while no differences were found for medium and long blinks (100–300 ms).

These results suggest that the introduction of a cognitive secondary task during a visual primary task induced an increase in eye blink frequency. This upward trend has been explained by the removal of the blink inhibition effect in dual-task conditions (Recarte et al., 2008; Veltman & Gaillard, 1996). The requirement to allocate attention to the secondary task is equivalent to reducing concentration on the primary one and impairs the blink inhibition process (Tsai et al., 2007). When a visual secondary task has to be performed concurrently, blink inhibition also seems to be removed but this seems to hold only for the shortest blinks (Benedetto et al., 2011).

In sum, the effects of varying driving environment on task demands and mental load are relatively well established. However, no study examined the effects of driving environment complexity on blink frequency. On the other hand, studies focusing on the effects of mental load on the blink frequency showed contrasting results depending on whether a single or dual task was carried out. In addition, the effects of dual task on blink rate are also dependent on the type of secondary task (Recarte et al., 2008; Savage et al., 2013). The present study was thus designed to vary systematically both the primary driving task demands (through the driving environment) and the cognitive secondary task demands, and then examine their combined effects on the blink rate. The main purpose was to assess eye blink behavior on their ability to identify whether drivers remain sensitive to the driving environment complexity when cognitive load increases. Based on previous studies (Benedetto et al., 2014; Hancock et al., 1990), we expected that blink rate would decrease with an increase in the driving environment complexity. The question that arises is whether or not this expected blink inhibition would resist the introduction of a cognitive secondary task. If the blink inhibition effect is preserved in spite of the introduction of a concurrent task, this would be evidenced by an absence or a lower blink increase in the most complex driving condition. An additional issue is whether the difficulty of the cognitive secondary task (i.e., simple reaction time task vs. complex calculation task) would affect the blink rate in different ways.

2. Methods

2.1. Participants

Twenty-four participants (20 males and 4 females) between the ages of 20 and 57 (mean age = 33.5 years; SD = 10) were recruited through advertisements on several forums. All of them had normal or corrected-to-normal vision and were naïve as to the aims and expected outcomes of the experiment. All participants declared they had a valid driving license with, on average, 14 years of driving experience (min = 2, max = 35, SD = 9.6) and drove a minimum of 3000 km per year (mean = 9500, max = 20,000, SD = 6500). Based on the given information about the experiment's general purposes, all participants signed an informed consent form about data recording of their driving performance, eye movements and subjective workload assessment before participating in the experiment. The study was approved by the IFSTTAR Ethics Committee.

2.2. Experimental setup

The experiment was run using the Sim2 driving simulator (Espié, Mohellebi, & Kheddar, 2003). The device included a cab, a one-screen image-generation system (resolution of 1280 × 960 pixels) and a 3D sound-rendition system. The cab included an adjustable seat, a steering wheel (Logitech G25) with force feedback, a gear lever, clutch, accelerator and brake pedals. Central and lateral mirrors were superimposed on the visual environment, along with a speedometer (Fig. 1). Data from the simulator were recorded at a frequency of 30 Hz. The simulated scene was displayed onto a 1.8 m wide × 1.3 m high white screen subtending a visual angle of 48 × 36 degrees, with participants facing the screen at a distance of approximately 2 m when seated on the simulator. The images (refreshed at 30 Hz) were calculated and projected at the participant's eye height, and the simulated viewing angle was aimed at the vanishing point of the simulated scenario.

Fig. 1. Illustration of the three driving environments (a – Highway; b – Rural driving; c – Urban driving).

Eye measures were recorded by means of a Pertech 50 Hz head-mounted monocular eye-tracker. A seven-point calibration was made for each participant and checked before each driving session. Room lighting was kept constant during all data acquisition sessions.

2.3. Experimental design and tasks

We used a within-subjects design with three driving environments (highway, rural environment and urban environment) and three dual task conditions (driving only, driving with a reaction time task, and driving with a calculation task). In total, there were nine experimental driving sessions.

Based on the classification of external demands that affect drivers' mental workload (Patten et al., 2004, 2006), the three driving environments were selected with the aim to trigger an increased demand upon information processing and/or vehicle handling. The highway environment consisted of a straight 2×2 carriageway located in the countryside with monotonous surrounding conditions (speed limit: 110 km/h), so that drivers were unlikely to be distracted by roadside environment and could control steering and speed in a consistent manner. Following Patten et al. (2004, 2006), this driving environment was supposed to trigger a low demand on information processing and a low demand on vehicle handling; mental workload imposed by this driving scenario was thus considered to be lower than the others. The rural environment represented a single carriageway winding road with standard white lane-markings (speed limit: 90 km/h). Road was lined with trees. Drivers had to negotiate a track with a series of right and left turns that were separated by a 100 m-long section of straight road. Bend length was comprised between 78 and 471 m and bend curvature was either 300 or 150 m. This scenario required a greater degree of steering control than the highway environment and was supposed to trigger a high demand on vehicle handling and a low demand on information processing. Lastly, the urban environment was designed to represent a neighborhood that was visually rich, with buildings, signs and traffic lights, as well as intersections, roundabouts and street furniture (speed limit: 50 km/h). Drivers had to adjust their trajectory as well as their speed as they progressed through the environment and had to pay attention to their surrounding environment when crossing intersections and roundabouts. This urban scenario was assumed to impose a high demand on information processing and a high demand on vehicle handling. In sum, the urban environment was expected to put higher task demands on drivers and to trigger higher workload level than the highway environment, with the rural environment giving rise to intermediate demands and workload. A snapshot of each driving environment is shown in Fig. 1. Finally, all these driving environments were free of traffic.

In each driving environment, participants were asked to perform the driving task as if they were driving in real road conditions and to conform to speed limits. The driving sessions in each environment lasted 3 min each.

In order to avoid confusion with the visual demands of the primary driving task (Savage et al., 2013), cognitive secondary tasks were selected and their level of difficulty was manipulated. A tone reaction time task was chosen as the secondary task with a low level of difficulty. It consisted of responding as rapidly as possible to an auditory stimulus (a "bip", 100 ms duration, 1.5 kHz amplitude) with a vocal response ("top"). The duration between each stimulus varied between 3 and 6 s to prevent any anticipation. This audio-vocal reaction time task was adapted from the standard PDT as one of its drawbacks is the occurrence of manual and visual interference with the primary task (Jahn et al., 2005). By selecting a simple reaction time task, the point of investigation was whether or not this kind of subsidiary secondary tasks does interfere with the driving task (see Hancock et al., 1990). This could be achieved by using the blink behavior as reference data.

Recarte et al. (2008) have shown that verbal production conditions such as talking and calculating can induce more blinks than verbal acquisition conditions; thus, we selected a mental arithmetic task as the secondary task with a high level of difficulty (e.g., Benedetto et al., 2014). In our experiment, participants were asked to add a two-digit number to a one-digit number. They then had to respond out loud as rapidly as possible. Calculations were separated by a 6 s interval (i.e., between voice offset and onset).

Auditory stimuli and calculations were pre-recorded. They were administered in a 3-min baseline condition (no driving) and during the dual task conditions where they were embedded into the engine sound. When performing the dual task conditions, participants were instructed to drive safely, as if they were operating in real road conditions, and to respond to the auditory stimuli as quickly as possible.

2.4. Procedure

The basic principles of the experiment were explained to the participants. Participants signed an informed consent form and demographic data was collected. The participants familiarized themselves with the tone reaction time task and mental arithmetic task. They were also invited to drive the simulator in various environments. This session was designed to allow them to become familiar with the handling of the pedals and steering in a variety of driving situations and maneuvers. The eye tracker was then calibrated. In the actual experiment, participants performed one session for each of the nine experimental driving conditions; these were presented in a random order. Before each session, the experimenter explicitly indicated to the participants the speed limit and the task condition (driving only, driving with a reaction time task, driving with a calculation task). The participants also performed the secondary tasks in a baseline condition (no driving). Half of them completed the baseline measures of the secondary tasks before the nine driving sessions, whilst the other half completed them afterwards. In each sub-sample, half of the participants performed the reaction time task before the calculation task and the other half did the opposite. Participants paused between the nine driving sessions in order to collect subjective ratings of mental workload (NASA-Task Load Index – NASA-TLX – Hart & Staveland, 1988). The whole experiment lasted approximately 1 h 30 min.

2.5. Data analysis

A multiple measures approach, which included eye blink, performance and subjective measures, was used. Eye blinks, driving behavior and subjective workload measures were collected for each driving session. Reaction times to the secondary tasks, as well as response accuracy to the mental arithmetic task, were recorded for each driving session and when the secondary tasks were administered in the baseline (no driving) condition.

2.5.1. Eye blinks

Studies which have defined the duration of a blink are scarce. Stern, Walrath, and Goldstein (1984) distinguished endogenous blinks from non-blink closures which are associated with sleep onset for instance. Endogenous blinks are characterized by (i) the time from initiation of the lid movement to full eye closure which takes generally around 100 ms, (ii) the period during which the vision is occluded which lasts at most 300 ms, and (iii) the full reopening phase lasting around 100 ms. Capitalizing on this, it was assumed that the longest endogenous blinks last 500 ms. Consequently, eye closure duration greater than 500 ms were considered non-blink closures and were excluded from our blink analysis. On the opposite, the lowest duration for a closure to be defined a blink is unclear. For example, the eyelid had to be closed during 70 ms in Benedetto et al. (2011), 80 ms in Benedetto et al. (2014), or 90 ms in McIntire, McKinley, Goodyear, and McIntire (2014) and this choice was based on the sampling frequency of the eye-trackers. We chose that the pupil had to be occluded for at least 80 ms to be considered as a blink. If the eyes were closed during less than 4 frames, it was considered a bad data set caused by the eye-tracker losing the pupil momentarily. Visual inspection of the row data coupled with inspection of videos of the eye reinforced the choice of this threshold. Blink events going from 80 to 500 ms were then captured by using a modified version of the algorithm developed by Pedrotti, Lei, Dzaack, and Rötting (2011) for low-speed eye-tracking studies. In accordance with Stern, Boyer, and Schroeder (1994), the blink rate (blinks per minute) was derived from the total number of eye blink events that took place in each 3-min experimental driving session. Based on the results of Benedetto et al. (2011) who suggested that visual task load mainly impacted short blink frequency, we also computed the median blink duration of each participant to explore whether more short blinks were made under high cognitive load conditions. In such case, median blink duration would decrease.

2.5.2. Secondary tasks performance

Participants' performance in the reaction time task corresponded to the temporal interval between the onset of an auditory stimulus and the verbal response. In the arithmetic task, because the duration of each stimulus was variable, the response time was defined as the temporal interval between the voice offset and the verbal response onset. When computing the mean response time (ms) for each dual-task driving session and the baseline condition session, we followed a procedure similar to Cantin et al. (2009). This consisted in removing the outlier data for each participant. Outliers corresponded to response times faster than 150 ms or slower than each participant's mean response time plus two standard deviations. The number of errors in the mental arithmetic task was also calculated.

2.5.3. Driving measure

Mimicking the characteristics of the three selected driving environments led to different speed limits and road width. Consequently, it was expected that driving speed would vary across driving environments due to their very nature and that lateral position deviation would be influenced by such road characteristics (e.g., Rosey, Auberlet, Moisan, & Dupré, 2009), inducing specific strategies in curves, intersections and roundabouts (e.g., Kountouriotis, Floyd, Gardner, Merat, & Wilkie, 2012), making difficult the comparison of speed and lateral position deviation between the three driving contexts. In order to have a proper measure to compare driving performance in the three driving environments, the steering reversal rate (SRR) was computed as it overcomes tactical aspects of the driving task (e.g., Frissen & Mars, 2014). SRR represents a true measure of the driving task difficulty and it has been validated as a measure of drivers' mental workload when driving becomes harder (Macdonald & Hoffmann, 1980; McLean & Hoffmann, 1975). When steering, slow movements allow following the desired path while faster movements allow correcting errors with respect to this trajectory (Donges, 1978). SRR measures the latter. It corresponds to the number of changes per minute in the direction of the steering wheel. A conventional threshold of 1° was used to detect reversals (e.g., Engström, Johansson, & Östlund, 2005; Jamson & Merat, 2005).

2.5.4. NASA-TLX

The NASA-TLX (Hart & Staveland, 1988) was intended to measure the operator's perceived workload along six dimensions: mental demand, physical demand, effort, own performance, temporal demand and frustration. We calculated the global score, which corresponded to the cumulative scores in each dimension.

The single driving condition (driving only) and the dual driving conditions with reaction time task and calculation task were labeled Single Task (ST), Dual Task Low (DTL) and Dual Task High (DTH) conditions, respectively. Statistical analyses were carried out with driving environment (highway, rural environment and urban environment) and dual task condition (ST, DTL and DTH) as within-participant factors. As we observed violations of the assumption of normal distribution in some of our data, we first ran non-parametric tests. These tests reported similar main effects and interaction as the repeated-measure analyses of variance (ANOVAs). Because the ANOVA is known to be robust against violations of the normality assumption and the risk of type I error (Glass, Peckham, & Sanders, 1972; Howell, 2010; Schmider, Ziegler, Danay, Beyer, & Bühner, 2010), we chose to report the repeated-measure ANOVAs. Sphericity violations were also explored and reported p values were adjusted following a Greenhouse–Geisser correction (Greenhouse & Geisser, 1959) when necessary. In such cases, epsilon (ε) which describes the degree to which sphericity has been violated, is given for the reader's information (the further ε decreases below 1, the greater the violation of sphericity). The significance level was set at 0.05 for all statistical analyses. The effect size (η^2) was also computed. Significant differences were further examined using the Fisher LSD post-hoc test when necessary.

3. Results

3.1. Eye blink frequency and duration

The driving environments (3) $\times$ dual task conditions (3) repeated measures ANOVA on the blink frequency revealed a main effect of the driving environment ($F(2,46) = 8.77$, $p < .01$, $\varepsilon = .72$, $\eta^2 = .28$) and dual task condition ($F(2,46) = 9.18$, $p < .01$, $\varepsilon = .81$, $\eta^2 = .29$). The interaction between both was not significant. Post-hoc test on the main effect of driving environment revealed that blinks were more frequent ($p < .05$) when driving on highway ($M = 11.8$ blinks/min) than when driving in urban settings ($M = 10.2$ blinks/min), which in turn triggered more blinks ($p < .05$) than when driving in rural curved roads ($M = 8.6$ blinks/min). The difference between highway and rural conditions was also significant ($p < .001$). Post test on the main effect of dual task condition revealed that more blinks were made ($ps < .001$) in the DTH condition ($M = 13.3$ blinks/min) than in ST ($M = 8.6$ blinks/min) and DTL conditions ($M = 8.7$ blinks/min) which did not differ ($p = .92$). The effects of driving environments and dual task conditions on eye blink frequency are depicted in Fig. 2.

The driving environments (3) $\times$ dual task conditions (3) repeated measures ANOVA on the median blink duration did not reveal any significant effect or interaction (all $ps > 0.6$). Median blink duration is given in Table 1.

3.2. Response times to the secondary tasks

A one-way ANOVA with reaction time in the DTL conditions as the dependent variable and four levels of the factor "driving environment" which included baseline returned a significant effect of this factor ($F(3,69) = 16{,}95$, $p < .0001$, $\eta^2 = .42$; see Table 1). Post test revealed that the vocal reaction time to the auditory stimulus in the no-driving baseline condition ($M = 365$ ms) was significantly lower than when driving whatever the road environment ($ps < .01$). Reaction time was not different ($p = .52$) between driving on highway ($M = 406$ ms) and driving on rural curved roads ($M = 399$ ms) but it increased in urban settings ($M = 449$ ms; $ps < .001$).

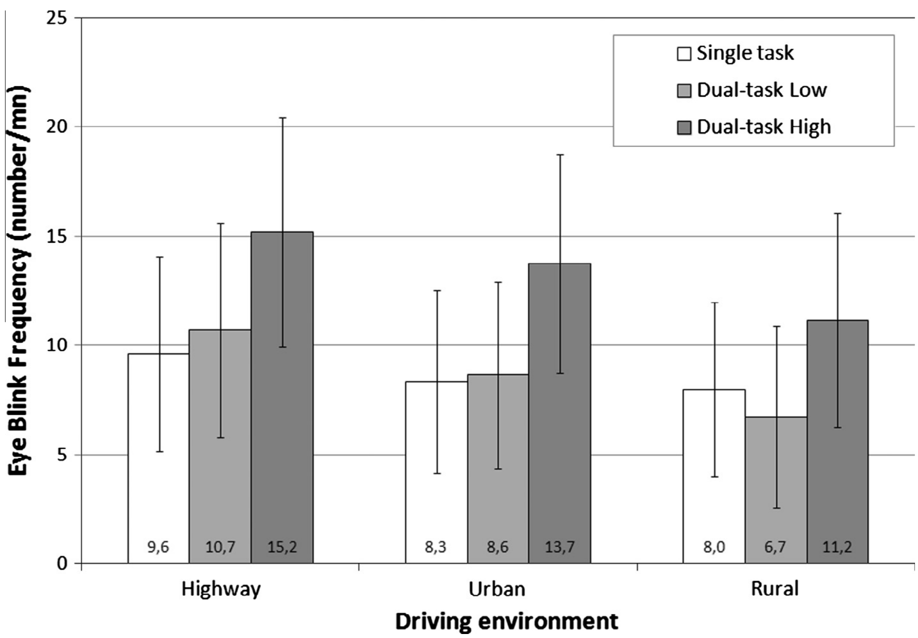

Fig. 2. Eye blink frequency in the three driving environments (Highway, Urban driving and Rural driving) and the three dual-task conditions (ST, DTL and DTH). Eye blink frequency corresponds to the number of blinks per minute. Error bars represent confidence intervals.

Table 1
Median blink duration (ms) and scores to the NASA-TLX in the nine experimental conditions, and response times (ms) to the audio-vocal and calculation tasks in the four environments (no-driving, highway, rural and urban driving). Between-subject standard deviations are given in brackets.

	Baseline (no driving)	Highway			Rural			Urban		
		ST[a]	DTL[b]	DTH[c]	ST	DTL	DTH	ST	DTL	DTH
Median blink duration (ms)	–	117 (20.8)	111 (24.1)	111 (17.2)	114 (22.9)	111 (23.8)	119 (41)	110 (25.5)	114 (26.6)	128 (35)
NASA-TLX	–	24.6 (12.8)	34.8 (19)	45.4 (23.8)	24.8 (12.9)	37.6 (20.5)	50.3 (23.8)	32.2 (16.4)	41.3 (21.7)	54 (26.7)
Reaction time task (ms)	364.8 (89)	–	406.1 (94)	–	–	398.6 (90)	–	–	448.9 (112)	–
Calculation task (ms)	721.8 (281)	–	–	765.5 (296)	–	–	811.2 (355)	–	–	855.9 (357)

[a] Single Task.
[b] Dual-Task Low.
[c] Dual-Task High.

A similar analysis was run on the mean response time in the mental arithmetic task which revealed a significant effect of the driving environment ($F(3,69) = 3,59$, $p < .05$, $\eta^2 = .13$; see Table 1). Post-hoc test revealed that response time was longer when calculating while driving in the urban environment than when calculating only ($p < .05$). There was no difference between the three driving environments ($ps > .11$).

The percentages of incorrect responses in the arithmetic task were 5.6%, 5.3%, 7.6% and 5% for the baseline, highway, rural and urban environments, respectively. These scores were not significantly different.

3.3. Steering reversal rate

The driving environments (3) × dual task conditions (3) repeated measures ANOVA on the SRR yielded a main effect of driving environment ($F(2,46) = 84.72$, $p < .0001$, $\varepsilon = .76$, $\eta^2 = .79$), dual task condition ($F(2,46) = 6.95$, $p < .01$, $\varepsilon = .79$, $\eta^2 = .23$) and an interaction between driving environment and dual task condition ($F(4,92) = 3.35$, $p < .05$, $\varepsilon = .68$, $\eta^2 = .13$). Participants made more steering corrections in the rural curved environment ($M = 25.9$ reversals per minute; $ps < .0001$) than in the urban ($M = 16.5$) and highway environments ($M = 9.8$), which also differed significantly from each other ($p < .0001$). The control of steering was also more difficult in the DTH condition ($M = 19.1$ reversals per minute; $ps < .05$) as compared to the ST ($M = 15.8$) and DTL ($M = 17.4$) conditions which did not differ from each other ($p = .07$). The interaction between driving environment and dual-task condition (Fig. 3) showed that SRR increased significantly with the increasing demand from the dual task condition in the rural environment ($ps < .01$). In the highway and urban environments however, only the difference between ST and DTH conditions was significant ($ps < .05$). Moreover, the effect of driving environment on SRR (as described above) occurred consistently in the three levels of dual-task conditions.

3.4. NASA-TLX

The analysis of the NASA-Task Load Index scores showed a main effect of the driving environment ($F(2,46) = 10.68$, $p < .001$, $\eta^2 = .32$) and dual task conditions ($F(2,46) = 26.13$, $p < .0001$, $\eta^2 = .53$). The interaction between both factors was not significant. Participants rated the workload as being higher in the urban area compared with the other two environments. The NASA-TLX scores also increased between the ST and DT conditions, as well as between the DTL and DTH conditions (Table 1).

4. Discussion

The goal of the present study was to vary systematically both the primary driving task demands (i.e., driving environment) and the cognitive secondary task demands to examine their combined effects on blink rate. Furthermore, it sought to assess in a multiple measure approach of mental workload the robustness of eye blink behavior to identify whether drivers remain sensitive to the driving environment complexity when cognitive load increases.

Overall, the findings confirmed that drivers' mental workload level increased with the complexity of the driving environment on one hand and with the introduction of a complex cognitive secondary task on the other hand. This was attested by the significant effects of these factors on eye blink frequency and steering reversal rate. However, results also revealed that (i) the present rural environment triggered a higher mental workload level than the urban environment, as suggested by the blink frequency decrease and the increment in the steering reversal rate in the rural environment, (ii) eye blink frequency suggests that drivers did not remain fully sensitive to the driving environment complexity when cognitive load increases, (iii) the effects on eye blink frequency and steering reversal rate converged when the primary task demands and the secondary task demands were varied one at a time, whereas there was a consistent dissociation between these measures

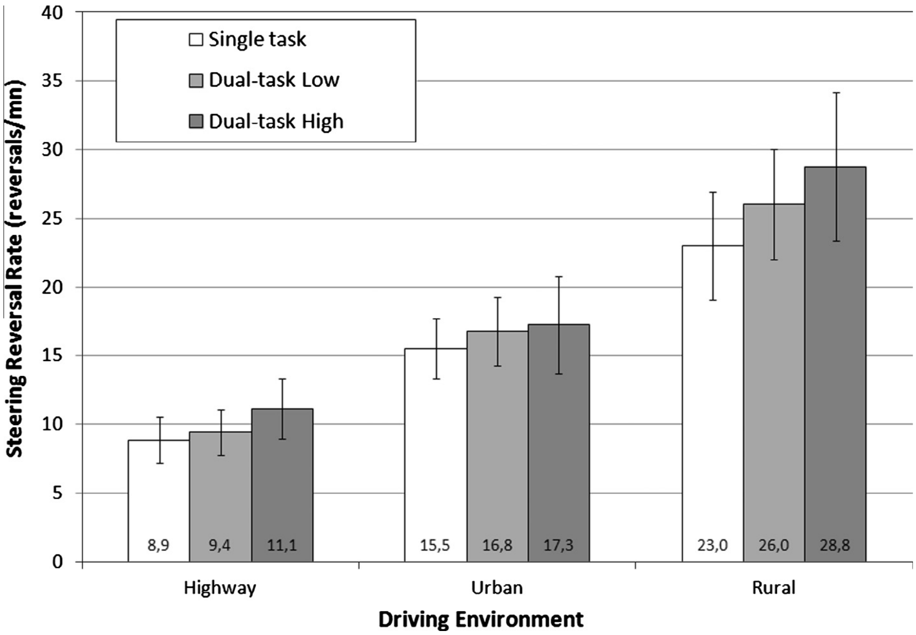

Fig. 3. Interaction between driving environments (Highway, Urban driving, Rural driving) and dual-task conditions (ST, DTL, DTH) on steering reversal rate. Steering reversal rate corresponds to the number of changes per minute in the direction of the steering wheel angle. A reversal corresponds to a change of 1° in the opposite direction. Error bars represent confidence intervals.

and subjective ratings of workload and performance to the secondary tasks. Each of these points is discussed in detail in the subsequent sections.

4.1. Driving environment

In line with previous research (Ariën et al., 2013; Jahn et al., 2005; Jamson & Merat, 2005; Patten et al., 2006; Törnros & Bolling, 2006; Verwey, 2000; Victor et al., 2005; Young et al., 2009), results confirmed that the complexity of driving environment impacted on drivers' mental workload level. What the present study adds is that eye blink frequency is a sensitive measure to elicit increased mental workload level coming from the driving context, as the blink frequency decreased when the driving environment was more demanding. This downward trend in the blink rate is in accordance with Bauer et al. (1985) or Veltman and Gaillard (1996) that the greater attention participants pay to task-relevant stimuli, the fewer endogenous blinks occur. Moreover degraded driving performance was also found when driving task complexity increased, as shown by significant differences between the three driving environments in the number of steering wheel corrections. This confirms the well known results that drivers' behavior is impaired when the driving task is more demanding (e.g., Jamson & Merat, 2005; Young et al., 2009).

Regarding the specific effects of driving environment, detailed results confirmed that driving freely on highway was the least demanding scenario (Patten et al., 2006; Victor et al., 2005; Young et al., 2009). However, they highlighted that the present rural environment triggered a higher mental workload level (less blinks were made) than the urban one. This is in contradiction with our predictions. Some inconsistency has already been shown regarding the respective effects of rural and urban driving contexts on mental workload measures. Törnros and Bolling (2006) showed that performance in a peripheral detection task was poorer in the urban than in the rural driving environment. On the contrary, Young et al. (2009) showed that steering control was more difficult and that the number of fixations outside the road was lower in the rural environment, visual tunneling being indicative of more workload (Tsai et al., 2007; Victor et al., 2005). With respect to Patten et al. (2004, 2006) who proposed that external demands of the driving task could be split between information processing demands and vehicle handling demands, the higher mental workload level found in the rural driving scenario could be explained by several factors. In the rural environment, (i) participants had to perform a series of bends which were separated by a 100-m long section of straight road; as such, they spent more time negotiating bends than driving on straight portions of road; (ii) in addition, steering control may have been quite demanding as bend curvature (150 and 300 m radius) was high, as compared for example with the study of Jamson and Merat (2005) where radius of curvature was comprised between 510 and 750 m. In the urban environment, (i) demands in terms of vehicle handling (intersections, round-about) were actually scarce, suggesting that increases in mental workload occurred only momentarily; (ii) the absence of traffic and interactions with other road users, either cars or pedestrians, which usually take place in urban settings may have reduced the intended load on information processing. That vehicle handling demands were high in the rural environment while in the urban environment vehicle handling and information processing demands were intermediate could explain the differences in mental workload level observed between the two driving scenarios. Results from the steering reversal rate showed that more steering corrections were made in the rural environment and are in line with the interpretation that vehicle handling demands were actually higher in this environment than in the urban one. On the other hand, the hypothesis that the absence of traffic and interactions with other road users may have reduced the intended load on information processing is supported by previous research showing that traffic complexity impacted on mental workload measures (Brookhuis et al., 1991; Hao et al., 2007; Teh et al., 2014) and that these measures were increasingly affected by the degree of interaction (e.g., Teh et al., 2014) or the criticality of the driving situation (e.g., Metz, Schömig, & Krüger, 2011).

4.2. Dual-tasking

Results showed that blink frequency increased in the DTH condition while there were no significant differences between ST and DTL conditions. This mental workload increase in the DTH condition was in addition accompanied by a degraded driving performance, as revealed by the higher number of steering wheel corrections in the dual driving and calculating task.

The present audio-vocal reaction time task was a modified version of the PDT procedure which has been extensively used in simulated or real driving to track mental workload. Both tests are auxiliary and indirect measure of workload and one of their drawbacks is that they are likely to interfere with the driving task (Jahn et al., 2005). As far as we know, it was the first time that this kind of task was screened with respect to the mental workload it induced on the operator. This was made possible by using unobtrusive measures such as blink behavior as reference data. The non-significant difference between ST and DTL conditions on the blink frequency suggests that a subsidiary secondary task did not place more workload upon drivers than a driving-only task. Furthermore, it did not impair the control of steering as steering wheel corrections did not differ significantly between ST and DTL conditions. This supports the idea that participants were able to perform both tasks at once and this might be explained by the absence of competitive resources as input and output sensory modalities differed between both tasks.

As expected, the blink increase in the DTH condition replicates previous results showing that blink frequency increased with the introduction of a cognitive secondary task (Benedetto et al., 2014; Recarte et al., 2008; Savage et al., 2013; Tsai et al., 2007). Our results also showed that the median blink duration did not change significantly across dual-task conditions. This confirms that increased cognitive load leads to higher blink frequency but does not affect blink duration (Savage et al., 2013). Other studies showed that increased visual workload led to shorter blink durations but did not vary blink rate (Ahlstrom & Friedman-Berg, 2006; Benedetto et al., 2011). As this suggests that visual and cognitive secondary tasks may have qualitatively different effects on eye blink behavior, there is a tentative suggestion that eye blink could provide a useful signature to distinguish the visual and cognitive origin of mental workload increase in driving.

4.3. Sensitivity to the driving environment with cognitive load increase

Results confirmed that eye blink frequency was affected in different ways depending on the sources of mental workload variations. When the driving environment was more demanding, blink frequency decreased, but it increased in dual-tasking. The question that remained unanswered is whether the blink inhibition would resist the introduction of a cognitive secondary task. In other words, it is unclear whether eye blink frequency is a robust measure of mental workload level when the primary task difficulty and dual-tasking are varied simultaneously.

First, the significant interaction between the driving environment and dual-task conditions on SRR confirmed that these two sources of mental workload had a cumulative effect on driving behavior. When the driving environment was more demanding, SRR increased, and it increased even more when drivers had to perform a cognitive secondary task concurrently. Although a downward trend in the eye blink frequency can be observed in the DTH condition when the driving environment was more demanding, which suggests that the blink inhibition was not completely removed under high cognitive load, the interaction between the driving environment and dual-task conditions on eye blink frequency was not significant. Combined with the SRR results as stated above, this confirms previous studies showing that drivers were not able to fully prioritize the primary driving task over the cognitive secondary task (e.g., Jamson & Merat, 2005). Whilst eye blink frequency seemed to be a robust measure to track drivers' mental workload when it is due either to the driving task demands or to the presence of a concurrent cognitive secondary task (Benedetto et al., 2014; Recarte et al., 2008; Savage et al., 2013; Tsai et al., 2007), the present results pointed out their poor reliability when it came to distinguish these sources of mental workload when they are varied simultaneously. This resulted in eye blink frequency that did not differ between driving in a demanding environment while performing a secondary task and driving freely in a low demanding environment.

4.4. Dissociation in a multiple measurement approach of mental workload

While the effects of varying in the same experiment both the primary driving task demands and the cognitive secondary task demands on eye blink frequency and driving performance converged, scores to the NASA-TLX and performance to the secondary tasks did not. Subjective workload estimates provide the most direct indicator of mental workload and have high face validity (e.g., Cain, 2007). However, Hart and Staveland (1988) noted that subjective ratings could be influenced by operator biases and preconceptions. In addition, Vidulich (1988) stated that subjective workload is only sensitive to manipulations that are well represented consciously. The dissociation found in the effects of driving environment on subjective ratings (participants' subjective estimates were higher in the urban environment than in the rural one) could possibly be explained by drivers' expectations and representations that driving in city centre requires more attentional resources. This erroneous representation of mental load has already been highlighted by Yeh and Wickens (1988) in their review of experiments which compared an easy dual-task condition to a more difficult single-task condition. They showed that operators did better in the easy dual-task condition but rated this condition as being more demanding than the single-task one. Erroneous representation of mental load could also explain the dissociation seen in the effects of dual-tasking between objective and subjective measures of workload. In the present experiment, the DTL condition was judged as being more demanding than the ST condition, although objective measure of workload and steering difficulty did not reveal any significant differences between these two conditions.

Regarding the effects of driving environment on response time in the DTL condition, our results revealed that mental workload level was lower in the highway and rural environments than in the urban one. This is in line with the results of Törnros and Bolling (2006) but it does not converge with eye blink and driving performance (SRR) data. Whereas PDTs are designed to be auxiliary, non-intrusive tasks as compared with loading, intrusive tasks, there is still a multitasking and competition issue between the primary and the secondary task (Cain, 2007). A very speculative hypothesis would be that participants might have prioritized the driving task over the subsidiary secondary task in the DTL/Urban condition presumably because of their preconceptions that driving in city centre is more demanding than any other driving contexts. However, this seems unlikely given that driving and reacting to the auditory stimuli may have been performed at once. Another explanation stems on the sensitivity of PDTs to mental workload variations. According to Jahn et al. (2005), PDTs are sensitive to short peaks in mental workload level unlike other methods that need to integrate raw data over longer intervals (see also Verwey & Veltman, 1996). The slower reaction time in the DTL/Urban condition could then come from momentary peaks of workload corresponding to the occurrence of the few driving difficulties implemented in this environment. This hypothesis is supported by the higher intra-individual variability of response time in the urban condition in comparison with highway and rural environments.[1] This suggests that eye blink frequency might then not be a suitable measure to detect such brief increases in drivers' mental workload.

Regarding the results on the DTH condition, performance in the calculation task was high and very similar across driving environments. As participants maintained their effort in carrying out the mental arithmetic, this should have led to a delayed response time when the driving task was more difficult. However, the difference between the three driving environments was not significant. These non-significant differences might have been due to the high inter-subject variability found in the response time to the calculation task. For this reason, it is difficult to conclude about the lack of convergence of this measure relatively to the others.

5. Conclusion

The present study was aimed at assessing the respective and combined effects of driving environment complexity and cognitive dual-tasking on eye blink behavior as a measure of drivers' mental workload variations. Results revealed that eye blink frequency was a sensitive measure to elicit increased mental workload level coming from the driving context. They also confirmed that the blink rate increased with the introduction of a cognitive secondary task but the median blink duration was not affected. These eye blink results expand those of previous studies showing that drivers were more loaded when driving task and dual-tasking demands increased, as shown in subjective workload estimates, driving behavior or eye-movement measures (e.g., Engström et al., 2005; Jamson & Merat, 2005; Victor et al., 2005; Young et al., 2009). However, our results also highlighted on one hand that eye blink behavior did not provide a clear mental workload signature when the driving task demands and the dual-task condition varied simultaneously and suggested on the other hand that it was not sensitive to brief increases in mental workload. Eye blink data were also highly variable (see also Benedetto et al., 2011) probably making difficult the building of models to classify cognitive load across individuals (Solovey et al., 2014). This overall picture tends to go against the suitability of eye blink behavior to monitor drivers' states at least when external and internal demands interact.

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[1] To explore whether reaction time was more variable in the DTL/Urban condition, we ran a one-way ANOVA with the within-subject standard deviation of reaction time in the DTL conditions as the dependent variable and four levels of the factor "driving environment", including baseline. This analysis returned a significant effect of driving environment, $F(3,63) = 5.48$, $p < .01$, $= .70$, $\eta^2 = .19$. The within-subject standard deviation of reaction time was larger in the urban condition ($M = 113$ ms) than in the three other conditions ($M = 72$, 80 and 71 ms, in the baseline, highway and rural conditions, respectively).

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