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Advanced Driver Assistance Systems:

Multimodal, redundant warnings enhance road safety.

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If you summon your courage

to challenge something,

you'll never be left with regrets.

How sad it is to spend your life wishing,

"If only I'd had a little more courage."

Whatever the outcome may be,

the important thing is to step forward on the path that you believe is right.

Daisaku Ikeda

To my family,
Ashley,
and my niece Anna.

Infinite gratitude to

Claudio
Riccardo and Massimiliano
Dave and Joel

for their precious support
throughout these last three years.

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Abstract

Advanced driver assistance systems or ADAS are designed to assist the driver while at the wheel of a motor vehicle. ADAS constantly monitor certain driving parameters such as the speed of the vehicle. When these parameters exceed safe threshold (e.g., the speed exceeds the limit), warnings are presented to inform the driver that the execution of given driving adjustments is needed in order to avoid likely accidents. Although ADAS may reduce accidents by 20%, if the warnings presented by these systems are poorly-designed, they may even disturb driving and, as a result, slow drivers' responses when fast, prompt reactions are instead needed. The aim of my doctoral dissertation is to measure the impact produced on driving by a number of warnings and, further, design a warning capable of speeding up drivers' responses without negatively affect subjective workload. For the execution of the seven experiments (4 in-lab and 3 driving experiments) contained in the dissertation, I considered the redundancy gain as theoretical framework and applied it to driving. I selected four types of warnings: unimodal visual, unimodal auditory, unimodal vibrotactile and multimodal (auditory + vibrotactile). Results showed that multimodal warnings were capable of reducing braking times even with drivers being distracted by a concurrent cell phone conversation or driving in dense traffic. In addition, no trade-off between braking times and subjective workload was found. These findings are of the utmost importance for car-manufacturers interested in enhancing the ADAS-driver interaction and, more broadly, for the entire research community working on automated vehicles.

Riassunto

I sistemi avanzati di assistenza alla guida o ADAS sono progettati per assistere il guidatore. Gli ADAS monitorano precisi parametri di guida come, ad esempio, la velocità del veicolo guidato. Quando questi parametri superano certe soglie (e.g., la velocità supera il limite), alcuni allarmi vengono presentati al guidatore. Tali allarmi hanno lo scopo di informare chi guida del fatto che determinate manovre devono essere eseguite per evitare che si verifichino incidenti. Sebbene gli allarmi presentati dagli ADAS siano capaci di ridurre gli incidenti del 20%, se tali allarmi non sono ben progettati, questi possono in realtà disturbare la guida e, di conseguenza, rallentare le risposte dei guidatori. Lo scopo della mia tesi di dottorato è quello di misurare l'impatto prodotto sulla guida da una serie di allarmi e di creare un allarme in grado di velocizzare le risposte dei guidatori e di non produrre alcun effetto negativo sul loro carico soggettivo. Per l'esecuzione dei sette esperimenti (4 esperimenti di laboratorio e 3 alla guida) contenuti nella tesi, ho considerato il fenomeno del redundancy gain. Ho identificato quattro allarmi differenti: visivi unimodali, acustici unimodali, vibrotattili unimodali e multimodali (acustici + vibrotattili). I risultati mostrano come gli allarmi multimodali siano in grado di ridurre i tempi di risposta dei guidatori anche durante l'esecuzione di un compito di telefonata e durante la guida in condizioni di traffico denso. Inoltre, nessun trade-off tra tempi di risposta e carico soggettivo è stato osservato. Questi risultati sono utili alle aziende automobilistiche interessate a migliorare l'interazione tra gli ADAS e il guidatore e, in maniera più ampia, per l'intera area di ricerca interessata ai veicoli automatizzati.

1 Distracted driving

Distraction is recognized as one of the main causes of mortality on the road. The National Highway Traffic Safety Administration reports that in 2009, in the United States only, more than five thousand individuals lost their lives on the road and 448.000 were injured in motor vehicle crashes involving distracted driving (NHTSA, 2010). Strayer, Watson and Drews (2011) distinguish between three different sources of distraction: manual, visual and cognitive. Manual distraction arises when drivers take their hands off the steering wheel to manipulate a device (e.g., handheld cellphone). Visual distraction occurs when drivers take their eyes off the road to interact with a device (e.g., in-car infotainment system). Finally, cognitive distraction arises when part of the driver' attentional resources is directed toward executing a secondary, driving-unrelated task and, therefore, withdrawn from the primary, driving activity.

These kinds of distraction have been objects of recent investigations. In 2012, for instance, the National Highway Traffic Safety Administration released a document containing an innovative methodology to measure the distractive impact of in-car manual and visual interaction technologies and guidelines to assist car-manufacturers while designing these devices (NHTSA, 2012). In more recent studies, Strayer, Cooper and colleagues (Cooper, Ingebretsen, & Strayer, 2014; Strayer, Cooper, Turrill, Coleman, Medeiros-Ward, & Biondi, 2013; Strayer, Turrill, Coleman, Ortiz, & Cooper, 2014) developed a framework to assess cognitive distraction and used it to measure the level of distraction associated with the execution of a number of every-day activities including cell phone conversations and interacting with speech-based technologies.

1.1 Distraction impairs driving. How?

The negative effects of visual, cognitive and manual distraction encompass a number of different driving activities. First, braking reaction times. In the study by Rossi, Gastaldi, Biondi and Mulatti (2012), participants drove a simulator and executed two different tasks. The first task was a cognitive task requiring participants to classifying words. The second task was a braking task: participants followed a vehicle and were instructed to brake as soon as the vehicle in front of them braked – car following paradigm (Ciuffo, Punzo, & Montatino, 2012). When the two tasks were executed together, compared to when they were executed separately, braking times were slowed and the stopping distance was elongated by about seven meters, long enough to cause a car accident at 80 kph. In addition to braking times, distraction impairs other aspects of the driver's latitudinal behavior. In the study by Strayer and Drews (2004), for instance, participants drove a simulated vehicle while engaged in a hands-free cell phone conversation. When talking on the cell phone, compared to the control condition (i.e., driving without distraction), the following distance (i.e., distance to the lead vehicle) increased by 12% and participants were observed to take longer to recover the speed lost during the braking. In a similar study, Haigney, Taylor and Westerman (2000) had participants driving a simulator and, at the same time, talking on a cell phone. When distracted, compared to the control condition, the mean speed decreased and, interestingly, became more variable.

Longitudinal (horizontal) control represents another aspect of driving being negatively affected by distraction. In the study by Ranney, Harbluck and Noy (2005), participants drove an instrumented vehicle and interacted with a dashboard-mounted multifunction information and entertainment system. Results showed that, when interacting with the system manually, participants reduced their control over the steering wheel and, as a consequence, the position occupied by the vehicle within the lane became more variable. Similar results were obtained in the study of Hosking, Young and Regan (2009) in which composing text-messages while driving was observed to increase the number of lane excursions, i.e., the number of times the driven vehicle moved out of the lane. Taken together, these findings suggest that manual, visual and cognitive distraction has a negative impact on safety by impairing drivers' behavior and making it more unpredictable to other road users.

1.2 Limiting the effects of distraction on safety

To reduce the adverse impact of manual, visual and cognitive distraction on safety, three are the main solutions being developed worldwide: educational programs to raise more responsible drivers, stricter regulations to keep drivers from executing risky behaviors and, at the vehicle level, advanced driver assistance systems or ADAS (Lu, 2006). ADAS are systems designed to constantly monitor the behavior of the vehicle and, if needed, inform the driver via emitting visual, auditory and, less often, tactile warnings (Damiani, Deregibus, & Andreone, 2009). Examples of ADAS are the rear-end collision avoidance system and the lane departure warning system. The former monitors the distance between different vehicles while the latter the position of the driven vehicle within the lane. When safety threshold are exceeded (e.g., distance between vehicles is too short or the driven vehicles moves out of the lane), warnings are presented.

Although assistance systems are designed to assist drivers, if warnings emitted by ADAS are poorly-designed, they may even disturb driving and, as a consequence, have a negative effect on safety. In the study by Dijksterhuis, Stuiver, Mulder, Brookhuis and de Waard (2012), for instance, participants drove a simulated vehicle equipped with a lane-departure warning system presenting information on a head-up display or HUD. The HUD is a visual display located in the driver’s side of the windshield and, therefore, within his/her visual field. Authors were interested in observing how the presence of the HUD affected driving performance and, therefore, whether the information provided by such a display could be beneficial to drivers. Although a benefit in terms of a better position maintained by the vehicle within the lane was found, over a third of participants claimed that, during the 30 minutes experiment, they tried to ignore the HUD as much as they could. Trying to ignore a given source of information and directing visual attention elsewhere requires a certain amount of cognitive resources (Logan, & Gordon, 2001) that, while operating a car, is necessarily taken away from the primary driving task. For such a reason, it is likely that employing visual displays as warning systems may produce negative effects on driving, especially if, as in the case of HUD, the information is presented within an area of the visual field used to detect road hazards. In another study, Adell, Várhelyi and Hjälmdahl (2008) had participants driving a simulated vehicle and were interested in measuring the effects of visual and auditory warnings on driving behavior. A red light flashing and an intermittent auditory stimulus (a beep) were presented to drivers every time the speed limit was exceeded. In addition, if the maintained speed was 20 kph or more over the limit, the beep became a continuous tone. The results showed that, although the warning system was capable of reducing speed, drivers judged it as annoying and irritating, feelings found to increase the tendency by drivers to discontinue the use of assistance systems (Jamson, Lai, & Carsten, 2008). Taken together, these evidences (see also Biondi, Rossi, Gastaldi, & Mulatti, 2014; Rossi, Gastaldi, Biondi, & Mulatti, 2013) suggest that, if poorly-designed, warning signals may impair drivers' behavior and, therefore, reduce road safety.

My doctoral dissertation aims to measure the effects of a number of different warnings on drivers' behavior. Experiments 1 to 5 measure the amount of dual-task interference produced by processing a number of warning signals on the execution of a braking task by considering the psychological refractory period (Pashler, 1994) as experimental paradigm. Experiments 6 and 7 investigate the effects produced by three different warnings on drivers' braking times and subjective workload with participants talking on a hands-free cellphone and driving in dense traffic.

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2 Multimodal stimuli to reduce dual-task interference.

The psychological refractory period or PRP is a well-known paradigm used in cognitive psychology to investigate the temporal microstructures and limitations of processes underlying dual-task performance (Pashler, 1994). In a dual-task context, participants are usually required to execute two tasks: t1 and t2. They are presented with two different stimuli – s1 and s2, and their task is to produce two different responses – r1 and r2. The presentation of s1 and s2 is separated by a time interval known as stimulus onset asynchrony or SOA. As the SOA is reduced the dual-task interference, that is the cost due to the concurrent execution of the two tasks, increases resulting in slower reaction times for t1, t2, or both.

Stimulus processing is constituted by perceptual, attentive and motor stages. Among these three, the locus of the dual-task interference is a matter of debate and each theory offers its own interpretation. Cross-talk theories (Navon & Miller, 1987) suggest that the cost arises when the two tasks involve similar information such as the same sensorial modalities. When s1 and s2 belong to the same sensorial modality (either visual, auditory or vibrotactile), we should observe a larger interference compared to when the modalities are different. Central capacity theories claim that the core of interference lies in the limited nature of the central, attentive stage of processing, where stimuli are processed and responses are selected. According to central capacity sharing theories (Tombu & Jolicoeur, 2005), the limited amount of central resources can be shared among tasks, with part of it allocated to t1 and the remaining part to t2. In contrast, central bottleneck theories (Pashler, 1994) – a specific instance of (not) sharing – suggest that the amount of central resource is to be entirely allocated to only one task at a time, either t1 or t2. Varying the SOA, the two theories predict different outcomes for RT1 and RT2 that are, respectively, reaction times for t1 and t2. For example, with a short SOA, the central capacity sharing predict an increase of both RT1 and RT2 compared to conditions with long SOAs. This is because, with short SOAs, the two tasks will both undergo the central stage of processing at the same time. With long SOAs, instead, when t2 enters the central stage, t1 may already have left it. In the same conditions, bottleneck theories predict that RT2 only will be subject to variations; RT1 will remain unaffected, no matter the SOA. The last group of dual-task interference theories comprise the motor bottleneck theories (De Jong, 1993). These claim the existence of a second bottleneck called response initiation bottleneck located after the central stage of processing. This bottleneck would prevent two different, discrete responses to be initiated in close succession.

The PRP paradigm has been applied to a number of real-life situations such as alcohol and caffeine consumption (Marczinski & Fillmore, 2006) and driving (Levy, Pashler, & Boer, 2006). In the study of Levy and colleagues, for instance, authors were interested in observing how the execution of a secondary task affected driving performance. Two tasks were considered. The first task consisted of indicating the number of times either a visual or auditory stimulus was presented. Participants produced their response either manually or vocally. For the second task, drivers followed a lead car and they had to brake every time the lead car’s brake lights went on. Results showed that, interestingly, as the SOA became shorter, RT2 slowed. The importance of this finding is twofold. First, it demonstrates that the PRP interference can be observed even within more realistic conditions. Second, it shows that even the completion of a simple, highly executed task as braking is not completely automatic and, as a consequence, it requires a certain amount of resources. The kind of resource – perceptual, attentive or motor - however, is still unclear. In the study by Rossi, Gastaldi, Biondi and Mulatti in 2012, authors had participants executing two tasks. For the first task, they listened to words and responded yes or no depending on whether the word belonged to a given category (semantic decision task) (Mulatti, Lotto, Peressotti, & Job, 2010). The second task consisted of a braking task. In the first experiment, authors replicated the finding of Levy and colleagues (2006). The second experiment was useful to investigate the source of the PRP interference. A go/no-go paradigm (Umebayashi, & Okita, 2013) was considered for t1: drivers were instructed to produce a vocal response only on half of the trials (go trials) and not on the other half (no-go trials). Results showed that, although reduced, the PRP interference was still present, with RT2 slowed as the SOA decreased. These findings suggest two different source of interference: one attentive, found in both the experiments, and one motor, found in experiment 1 only when t1 required a motor response.

This study is part of a broader project conducted in collaboration with Prof. Rossi and Prof. Gastaldi (Transportation Lab, Department of Civil Engineering, University of Padova) aimed to measure and possibly reduce the impact produced by the presentation of warnings on drivers’ behavior. In particular, in the five experiments here presented, we are interested in measuring individuals’ performance and subjective workload while responding to the presentation of visual, auditory, vibrotactile and multimodal stimuli. Authors considered the psychological refractory period as experimental paradigm and two different tasks: a stimulus response task and a braking task. Following is an overview of the five experiments.

Experiment #	**Stimuli for task 1**	**Task 2**	**Environment**
1	Visual stimuli	Surrogate braking task	Laboratory
2	Auditory stimuli	“	“
3	Vibrotactile stimuli	“	“
4	Multimodal (auditory + vibrotactile) stimuli	“	“
5	Auditory, vibrotactile and multimodal stimuli	Braking task within the car-following paradigm	Driving simulator

Table 1. Overview of the five experiments contained in this chapter. Task 1 is a stimulus response task and the table shows the stimuli used for this task across experiments. Task 2 is a surrogate braking task in exp. 1 to 4 and a braking task in exp. 5. Exp. 1 to 4 took place in a controlled environment with participants sitting in front of a computer. Experiment 5 took place in a driving simulator.

2.1 Experiments 1 to 3

Experiments 1 to 3 measure the interference produced by responding to visual (exp.1), auditory (exp.2) and vibrotactile (exp.3) stimuli on the execution of a surrogate braking task. In particular, we aim to find out which of the three modalities considered for the first task produces the smallest degree of interference in terms of reaction times, accuracy and subjective workload.

As task 1, we consider a stimulus response task: after the presentation of a stimulus, participants are instructed to produce a button press. The modality of this stimulus varies across experiments. As task 2, we consider a surrogate braking task: participants respond to the presentations of a red circle displayed on a computer monitor by pressing a pedal with their right foot.

METHOD

Participants

Experiment 1. Sixteen undergraduate students (6 women, 10 men) at the University of Utah, USA, participated in the experiment 1. The average age was 24 years with a standard deviation of 3.7 years. Thirteen participants were right-handed, three left-handed.

Experiment 2. Sixteen undergraduate students (7 women, 9 men) at the University of Utah, USA, participated in the experiment 2. The average age was 25 years with a standard deviation of 3 years. Eleven were right-handed, four left-handed.

Experiment 3. Sixteen undergraduate students (7 women, 9 men) at the University of Utah, USA, participated in the experiment 3. The average age was 25 years with a standard deviation of 4.3 years. Nine were right-handed and six left-handed.

All the participants in every experiments had a normal or correct-to-normal vision. They did not make use of any hearing device and did not report having hearing deficits. All of them possessed a valid driving license.

Design and Procedure

For the first task, participants were presented with visual (experiment 1), auditory (experiment 2) and vibrotactile (experiment 3) stimuli and responded by pressing a key on the keyboard. For the second task, participants were presented with a red circle and responded by pressing a pedal with their right foot, the same effector used to brake while driving. Six experimental blocks were considered. B1, b2 and b3 were single-task blocks. In these blocks, participants executed the two tasks separately. In b1 and b2, the first task was a simple reaction time task – only one possible stimulus, one response. In b3, the first task was a choice reaction time task – a stimulus chosen from two possible stimuli, two different responses. B4, b5 and b6 were dual-task blocks. In b4 and b5, the first task was a simple reaction time task and in b6 it was a choice reaction time task. T2 was always a simple reaction time tasks. B1, b2 and b3 were composed by one session of 55 trials each. B3, b4 and b5 were composed by two sessions of 55 trials each. Each session was composed by 20 trials for t1, 20 for t2 and 15 fillers (no stimuli were presented). Each experimental block was preceded by the execution of 10 practice trials. The SOA considered for the dual-task blocks were: 150ms, 300ms, 600ms and 1200ms. The responses for t1 were executed by pressing either one or two keys with the middle and index fingers of the same hand. The fingers (middle/index) and hands (left/right) used to produce r1 and the position of the stimuli on the monitor (left/right half) were counterbalanced across participants.

Participants were sitting 80cm from the monitor. At the beginning of the experiment they were presented with instructions. They were instructed to respond to the stimuli as quickly and accurately as possible. After each and every experimental block, participants' subjective workload was measured via the six NASA-TLX scales. Subjective workload, reaction times and accuracy rate were the dependent measures. The experiment had a duration of 45 minutes.

Apparatus and stimuli

The experiments were executed using a Dell Optiplex 745 pc running Windows Vista connected to a Dell 23 inches LCD monitor (1920x1080 pixels resolution). The software used to design the experiments, present stimuli and collect responses was E-Prime version

2.0 (PST Inc.). For the second tasks, participants were presented with the letter ‘O’ (Courier New 30 font) in red on a white background, displayed with a visual angle of 1x1 degrees on the center of either the right or left half of the monitor. Responses were collected through a foot pedal (PST, Inc. Foot Pedal) connected to the pc via a Serial Response Box (PST, Inc.). Stimuli used for the first task varied across experiments. The stimuli for t1 used in experiment 1 were the ‘#’ and ‘X’ symbols (Courier New 30), presented in black on a white background with a visual angle of 1x1 degrees. The symbols were presented at the center of the right and left half of the monitor; the position of each symbol was counterbalanced across participants. The stimuli used in experiment 2 were two tones: a high (900 Hz) and a low tone (300 Hz) presented binaurally for 200ms over headphones at approximately 50 db. The vibrotactile stimuli used in experiment 3 were vibrations (amplitude 0.5 G and duration 200ms) produced by Lily Pad Vibe motors. A motor was placed on each of the participants’ hands. The motors were attached to an Arduino board connected to the Serial Response Box. I built the customized device and wrote the C++ code with the assistance of Joel Cooper (Precision Driving, Salt Lake City, Utah). Subjective workload was measured by using the NASA-TLX (Hart & Staveland, 1998) It comprises six 21-points scales: mental (How mentally demanding was the task?), physical (How physically demanding was the task?), temporal ((How hurried or rushed was the pace of the task?), performance (How successful were you in accomplishing what you were asked to do?), effort (How hard did you have to work to accomplish your level of performance?) and frustration (How insecure, discouraged, irritated, stressed, and annoyed were you?).

RESULTS

Reaction times

RT were screened for outliers. In particular, for each participant, reaction times exceeding 2.5 standard deviations from the participant’s mean were removed and not further analyzed. In each of the following experiments, less than 5% of the data were excluded as outliers. Multiple repeated measures analysis of variance (ANOVA) were performed on reaction times data. The Greenhouse-Geisser correction was adopted. Reaction times to task 1 measured in experiments 1 to 3 are presented in table 2.

Modality	**Single-task**	
	T1 simple	T1 choice
Visual	474.09	516.52
Auditory	411.92	488.06
Vibrotactile	368.42	464.29

Table 2. Reaction times (in milliseconds) to task 1 as simple and choice tasks in single-task conditions and across experiments with visual (exp.1), auditory (exp.2) and vibrotactile (exp.3) stimuli.

Task 1. Single-task RT1 were compared across experiments 1, 2 and 3. With t1 as a simple reaction time task, a significant main effect of experiment (1, 2 and 3) was found, F (2, 30) =5.6, p<.05, $p\eta^2$=.27. RT1 with visual stimuli (experiment 1) were found to be significantly slower than those in experiment 2 and 3. Further, no significant differences were found between RT1 with auditory and vibrotactile stimuli. The same analysis was performed with t1 as a choice reaction time task. A significant main effect of experiment was found, F (2, 30)=15.6, p<.05, $p\eta^2$=.51. In particular, rt1 with vibrotactile stimuli were found to be significantly faster than those with auditory and visual stimuli. No significant difference was found between rt1 with visual and auditory stimuli, p>.05.

Dual-task RT1 were analyzed by performing repeated measure ANOVAs with experiment (experiment 1, 2 and 3) as a between-subject and SOA (150ms, 300ms, 600ms, 1200ms) as a within-subject factors. With t1 as simple reaction time task, no significant main effect of SOA were found, indicating that RT1 are not affected by SOA. Also, a significant effect of experiment was found, F (3, 45)=4.3, p<.05, $p\eta^2$=.22, with RT1 with vibrotactile stimuli being faster than those with auditory and visual stimuli. The same analysis performed with t1 as choice reaction time task revealed no significant main effect of SOA but significant main effect of experiment, F (2, 30)=20.4, p<.05, pη^2=.57, with RT1 with vibrotactile stimuli being faster than those with auditory stimuli (p<.05), and RT1 with auditory stimuli being significantly faster than those with visual stimuli, p<.05.

Task 2. No significant differences were found between RT2 across experiments within single-task blocks, F (2, 30)=2.5, p>.05. For RT2 measured in dual-task blocks, a repeated measures ANOVA with experiment (1, 2 and 3) as between subject factor and SOA as within subject factor was performed. With t1 as simple reaction task, significant main effects of experiment, F (2, 30)=8.3, p<.05, pη^2=.35, SOA, F (3, 45)=245, p<.05, pη^2=.94, and interaction, F (6, 90)=4.3, p<.05, pη^2=.22, were found. The same analysis was performed with t1 as choice reaction time task and significant main effects of experiment, F (2, 30)=15.5, p<.05, pη^2=.50, SOA, F (3, 45)=481.4, p<.05, pη^2=.97, and interaction, F (6, 90)=19.1, p<.05, pη^2=.56, were found. These patterns of results suggest that, as expected, as the SOA decreases, RT2 increase and, interestingly, the reduction in RT1 observed for auditory and vibrotactile stimuli propagate onto RT2 with t1 as both simple and choice task.

Blocks	**SOA**			
Simple	*150*	*300*	*600*	*1200*
Exp.1	524.13	433.88	338.70	322.94
Exp.2	409.33	308.90	276.61	268.69
Exp.3	389.98	305.50	269.16	258.61
Choice				
Exp.1	761.25	624.90	432.39	331.14
Exp.2	544.50	416.85	305.00	283.50
Exp.3	487.94	373.40	268.58	266.94

Table 3. Reaction times for task 2 in dual-task conditions across SOA and experiments and within blocks with t1 as simple and choice reaction time task.

Accuracy

Accuracy rate for t1 was calculated as the number of error executed by participants divided by the number of trials. As expected, participants committed more errors with t1 as choice reaction time task. Although no significant differences were found between experiments 1, 2 and 3, an increase in error rate was found when auditory stimuli were considered (12% compared to 5% for both visual and vibrotactile stimuli).

Subjective Workload

Repeated measures ANOVA with experiment (1,2 and 3) as between-subject factor and experimental block (4: single-t1 simple, single-t1 choice, dual-t1 simple, dual-t1 choice) as within-subject factor were executed for each of the six scales of the NASA-TLX. Significant main effect of experiment was found for mental workload, $F(2, 30)=16.9$, $p<.05$, $p\eta^2=.53$, and effort, $F(2, 30)=7.5$, $p<.05$, $p\eta^2=.33$. In particular, processing auditory stimuli was found to be less mentally demanding and require less effort than processing visual and vibrotactile stimuli (no significant differences between these two last modalities).

DISCUSSION

Vibrotactile and auditory stimuli appear to be those producing faster and less demanding responses. In particular, with t1 as simple reaction time task, processing vibrotactile and auditory stimuli required, respectively, 100ms and 60ms less that processing visual stimuli. Similar patterns of results were observed across all experimental condition. In dual-task blocks, for instance, with t1 as choice reaction time task the benefit obtained by using vibrotactile stimuli was even larger. Compared to visual stimuli, a reduction of about 250ms was observed across SOAs with vibrotactile stimuli and a reduction of about 120ms was observed with auditory stimuli. These results suggest that, although the dual-task interference was not eliminated, using not-visual stimuli for t1 may significantly reduce the interference produced by this task on the execution of the surrogate braking task. Such a finding, in line with cross-talk theories (Navon & Miller, 1987), have important implications for cognitive psychology applied to driving.

In recent years, an increasing number of studies focused on how to make the interaction between the driver and in-car technologies safer through using warnings that are not visual (Baldwin & Lewis, 2013; Mohebbi, Gray, & Tan, 2009; Medeiros-Ward, Cooper, Doxon, Strayer, & Provancher, 2010). This is because the visual channel is already heavily taxed while driving and adding additional burdens may likely produce high levels of distraction and, as a result, accidents (NHTSA, 2012). In the study by Sodnik, Dicke, Tomazic, and Billinghurst (2008), for instance, authors had drivers interacting with a mobile device presenting information to them either visually or auditorily. Results showed that when the information was presented visually on a LCD screen on the dashboard, the driving performance worsened and perceived workload increased. In a similar study, Mohebbi, Gray ad Tan (2009) instrumented a driving simulator with a rear-end collision warning system that is a system monitoring the distance between the driven and the followed cars and emitting warnings when such a distance falls under a threshold. Participants were presented with either vibrotactile or auditory warnings. Results showed that vibrotactile warnings were more effective than auditory in terms of eliciting faster braking reaction times and fewer collisions. Our data strongly support the findings obtained in these studies. In addition, our data suggest that, although vibrotactile stimuli may produce faster response, using auditory stimuli may produce a benefit in terms of reduced mental workload and effort. But, what happens when these two types of stimulation are combined together?

2.2 Experiment 4

Within a simple reaction time context, the redundant target effect (Forster, Cavina-Pratesi, Aghlioti, & Berlucchi, 2002) is a facilitation in terms of response times obtained as a consequence of presenting, instead of only one stimulus, multiple stimuli with different modalities. Race models (Raab, 1962) suggest that the presentation of multiple stimuli with different modalities produce separate parallel activations in different sensory channels. The channel that reaches the response level first, it triggers the response. The resulting response times are therefore expected to be similar to those produced by the faster stimulus among those considered. A second account for this effect comes from coactivation theories

(Diederich & Colonius, 1987). Coactivation theories claim that the facilitation obtained by the presentation of multiple, concurrent stimuli is a result of the convergence of the incoming signals triggering a unique response. Given $\mathrm{minRT}_{\mathrm{AND}}$ and $\mathrm{minRT}_{\mathrm{OR}}$ as the minimum reaction times resulting from, respectively, presenting multimodal and unimodal stimuli, a situation with $\mathrm{minRT}_{\mathrm{AND}} < \mathrm{minRT}_{\mathrm{OR}}$ would argue in favor of coactivation theories. A different pattern of results, on the other hand, might support race models.

In the fourth experiment we measure how the concurrent presentation of multimodal stimuli for t1 affects the PRP performance. As stimuli, we consider those that produced the best performance in the previous experiments: vibrotactile and auditory. Also, we considered two different conditions: OR and AND. In the OR condition participants are presented, within the same experimental block, with either vibrotactile or auditory stimuli. In the AND condition, instead, these stimuli are presented at the same time. This experiment aims, first, to investigate how the presentation of multiple stimuli affects RT1 within both the OR and AND conditions. Second, if a facilitation is found, how that would affect dual-task interference. It is indeed plausible that the redundancy gain for t1 may reduce that cost and, possibly, eliminate it. Third, by administrating the NASA-TLX at the end of experimental block, we aim to investigate how the subjective workload is affected by multimodal stimuli. A trade-off between response time and workload needed to process the stimuli is foreseen.

METHOD

Participants

Sixteen undergraduate students (10 man, 6 women) at the University of Utah participated in this experiment. Their average age was 24 years and the standard deviation was 3.7 years. All the participants were right-handed and had a normal or correct-to-normal vision. They did not make use of any hearing device and did not report having hearing deficits. They all possessed a valid driving license.

Design and Procedure

The second task was identical to previous experiments with participants pressing a pedal with their right foot in response to the presentation of a red circle on the computer monitor. For the first task participants responded to the presentation of a vibration and a sound presented either separately (OR condition) or together at the same time (AND condition) by producing button-presses as in previous experiments. A graphical representation of the OR and AND conditions are presented in figure 1.

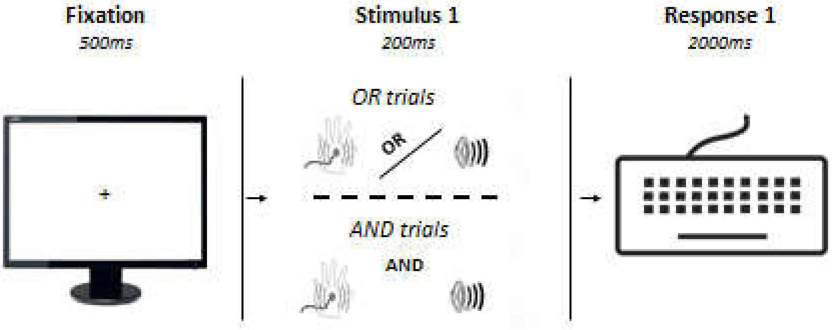

Figure 1. Participants were presented with a fixation cross for 500ms. In OR trials, it was followed by the presentation of either a vibration or a sound – they were never presented concurrently. In AND trials, the fixation cross was followed by the concurrent presentation of both the sound and the vibration. In both the conditions, the stimuli were presented for 200ms. In response to the presentation of either the vibration or the sound in OR trials, or both the vibration and the sound in AND trials, participants had 2000ms to press the appropriate key on the keyboard.

Six experimental blocks were considered. B1 and b2 were single-task blocks and b3, b4, b5 and b6 were dual-task blocks. In b1, vibrations and sounds for t1 were presented separately (OR); in b2, vibrations and sounds were presented together (AND). In b3, sounds and vibrations were presented separately – OR block, and in b4, sounds and vibrations were presented concurrently – AND block. In b1, b2, b3 and b4 participants responded to the presentation of the stimuli by pressing a unique key on the keyboard. B5 and b6 were dual-task blocks with t1 as a choice reaction time task. In b5 and b6, participants were presented with two stimuli: s11 and s12. In b5 (OR block), s11 was either a vibration or a sound; in b6

(AND block), s11 was a vibration and a sound presented together. In both b5 and b6, s12 was a visual stimulus (‘#’, same characteristics as in experiment 1); we decided to consider a visual stimulus and no other vibrotactile or auditory stimuli to keep the instructions easy and, therefore, not overcomplicate the experiment. If presented with s11 participants pressed a given key; if presented with s12, they pressed a different key. Importantly, we considered t1 as choice reaction time task only within dual-task blocks; considering t1 as choice task even within single-task blocks was considered unnecessary given the aims of this study and, in addition, it would have overextended the duration of the experimental session. B1 and b2 were composed by 55 trials each. B3, b4 and b5 were composed by two sessions of 55 trials each. Each session was composed by 20 trials for t1, 20 for t2 and 15 fillers (no stimuli were presented). Each experimental block was preceded by the execution of 10 practice trials. Within AND blocks, vibrations and sounds were never presented separately. The SOA considered for the dual-task blocks were 150ms, 300ms, 600ms and 1200ms.

Apparatus and stimuli

Apparatus and stimuli were similar to those used in previous experiments. The only difference is that, in the AND condition, vibrations and sounds were presented at exact the same time whereas in the OR condition they were presented singularly.

RESULTS

RT were screened for outliers. In particular, reaction times exceeding 2.5 standard deviation from the mean were removed and not further analyzed. In each of the following experiments, less than 5% of the data were excluded as outliers. Repeated measures ANOVAs were performed on reaction times data. The Greenhouse-Geisser correction was adopted.

Reaction times

Task 1. In the single-task block, a pairwise comparison, t (15)= 6.12, p<.05, revealed that RT1 in the AND condition were faster compared to those in the OR condition. Similar patterns of results were found in the dual-task blocks. A repeated measures ANOVA with conditions (2 levels: OR and AND) and SOAs (4 levels) showed that RT1 in the AND condition were faster compared to those in the OR condition, F(1,15)=23.5, $p<.05$, $p\eta^2=.61$. Further, a significant effect of SOA, F(3,45)=15.7, $p<.05$, $p\eta^2=.51$, showed that RT1 increased as SOAs decreased in both AND and OR conditions. Minimum RT1 were calculated across conditions and SOAs to test for the coactivation hypothesis. Minimum reaction times were shorter in the AND condition compared to the OR condition across all SOAs. RT1 in single-task blocks are shown in table 4.

Modality	**Single-task**
	T1 simple
Multimodal OR	349.42
Multimodal AND	264.17

Table 4. RT1 with t1 as simple and choice reaction time task (in ms) across experimental blocks with multimodal OR and multimodal AND stimuli.

In their 2004 study, Diederich and Colonius, described the so-called multisensory response enhancement (MRE) as a measure to quantify the percentage of RT enhancement obtained within redundant target effects context. Following their study, MRE is calculated in this experiment as follows:

$$\mathrm{MRE} = \frac{\overline{\mathrm{RT}}_{\mathrm{OR}} - \overline{\mathrm{RT}}_{\mathrm{AND}}}{\overline{\mathrm{RT}}_{\mathrm{OR}}} \times 100$$

Table 5 shows the MRE calculated across experimental conditions and SOAs.

	Condition							
	T1 simple task				T1 choice task			
SOA	*150*	*300*	*600*	*1200*	*150*	*300*	*600*	*1200*
MRE	42.70	46.81	63.55	58.66	22.63	25.90	28.63	32.14

Table 5. Multisensory Response Enhancement (MRE) calculated according to Diederich and Colonius (2004) across conditions and SOA in dual-task conditions.

Task 2. RT2 with t1 as simple task were compared across AND and OR conditions. A repeated measures ANOVA with conditions (2 levels) and SOA (4 levels) as within-subject factors revealed significant main effects of condition, F(1, 15)=23.4, p<.05, $p\eta^2$=.61, SOA, F(3, 45)=15.7, p<.05, $p\eta^2$=.51, and interaction, F(3, 45)=10.1, p<.05, $p\eta^2$=.402. In particular, RT2 in the AND condition were found to be faster than those in the OR. Same analysis were performed on RT2 with t1 as choice task. Interestingly, no main effect of condition was found (F<1), suggesting that the redundancy gain disappear with more complex tasks. Significant effect of SOA was found, F(3, 45)=48.7, p<.05, $p\eta^2$=.76.

Blocks	**SOA**			
Simple	*150*	*300*	*600*	*1200*
Multimodal OR	468.18	373.43	323.79	301.37
Multimodal AND	345.52	273.39	245.13	238.45
Choice				
Multimodal OR	528.84	414.70	285.54	283.10
Multimodal AND	459.05	376.39	313.95	284.72

Table 6. Reaction times for task 2 in dual-task conditions across SOA and multimodal conditions (OR and AND) and within blocks with t1 as simple and choice reaction time task.

Accuracy

In dual-task conditions and with t1 as simple task, more errors were executed in OR condition than in AND condition, F(1, 15)=9.6, $p<.05$, $p\eta^2=.39$. Same pattern of results with t1 as choice task, F(1, 15)=8.6, $p<.05$, $p\eta^2=.36$. This suggests that presenting multimodal stimuli together (AND), compared to when presented separately (OR), produce a benefit in both response times and accuracy.

Subjective Workload

Repeated measures ANOVA with condition (2 levels: AND and OR) and experimental block (4: single-t1 simple, single-t1 choice, dual-t1 simple, dual-t1 choice) as within subject factors were executed for each of the six scales of the NASA-TLX.. Significant main effect of condition was found for temporal workload only, F(1, 15)=16.9, $p<.05$, $p\eta^2=.53$. In particular, participants felt more rushed in the AND condition than in the OR condition. No significant effects for mental workload and effort were found, suggesting that responding to multimodal stimuli did not produce an increase in workload compared to the OR condition.

DISCUSSION

Presenting concurrent multimodal stimuli speeds up response times. Response times in the AND condition were found to be significantly faster than those in the OR condition (see table 6). In addition, minimum response times in the AND condition were always faster than those in the OR condition. These results rule in favor of the coactivation theory according to which unimodal signals, when presented together, are combined to jointly trigger a unique response. To quantify such a facilitation across experimental conditions and SOAs, we calculated the multisensory response enhancement or MRE (Diederich & Colonius, 2004) that is an index measuring the percentage of RT enhancement within redundant target contexts. MRE are shown in table 5. An average MRE of 52% was found with t1 as simple task. This means that with redundant targets, compared to single stimuli, response times are sped up by 52%. A smaller MRE (average 27%) was found with t1 as choice task. This difference suggests that as the first task becomes more difficult, the facilitation is reduced, likely because, in this case, a longer time is anyway needed to select the response at the central stage of processing. Another interesting findings concern the SOA. As the SOA increases, an even larger MRE was found, especially with t1 as simple task. The cause does not have to be searched in RT1 in the OR condition (not different across SOAs), but in those recorded in the AND condition. Shorter RT1 were found with long. SOAs. This result is consistent with central sharing theories (Tombu and Jolicoeur, 2005) and represents the reason why a MRE of 58% was observed with SOA of 1200ms.

	Condition			
	T1 simple task		T1 choice task	
	OR	*AND*	*OR*	*AND*
PRP interference	166.82	77.07	245.74	174.33

Table 7. PRP interference across experimental conditions. PRP interference is calculated as the difference in mean RT2 between 150ms and 1200ms SOA (Van Selst, Ruthruff, & Johnston, 1999).

Another important implications of our data concerns the PRP interference. It was indeed hypothesized that if the presentation of multimodal stimuli led to faster reaction times, a reduction in the PRP interference should have to be observed. Looking at table 7, we can indeed see that, with T1 as simple task, the PRP interference in the AND condition was less than the half compared to that in the OR condition (77ms vs.166ms). This suggests that presenting redundant targets reduced - but never eliminated - the magnitude of the dual-task interference.

Interesting results were also obtained for accuracy and subjective workload. A larger amount of errors were committed in the OR condition, compared to the AND condition. This suggests that the benefit obtained by the concurrent presentation of multimodal stimuli is not limited to response times only but it also extends to the quality of the performance.

This finding is quite surprising if we consider that a trade-off between accuracy and speed is usually observed in literature (MacKay, 1982). About subjective workload, no substantial differences were found between OR and AND conditions. This suggests that responding to multimodal stimuli presented together produces similar levels of workload compared to when they were presented separately.

2.3 Experiment 5

This PRP experiment aims to replicate the findings obtained in the fourth experiment but within a driving environment. In particular, we are interested in observing whether the benefits associated to the presentation of multimodal warnings may be observed even with participants at the wheel of a simulated vehicle. Although results obtained in controlled environments are often replicated within more applied contexts (Strayer, Cooper, Turril, Coleman, Medeiros-Ward and Biondi, in press), it is still possible than adding a highly complex task such as driving, even if simulated, may likely affect drivers' performance in dual-task experiments.

METHOD

Participants

Twenty-two undergraduate students (10 man, 12 women) from the University of Utah participated in this experiment. Their average age was 22 years and the standard deviation was 2.7 years. All the participants were right-handed and had a normal or correct-to-normal vision. They did not make use of any hearing device and did not report having hearing deficits. They possessed a valid driving license from an average of 6.7 years.

Design and Procedure

Participants executed two task according to the PRP paradigm. For the first, simple reaction time task, they were presented with either auditory, vibrotactile and multimodal stimuli in, respectively, experimental block 1, 2 and 3 (stimuli for task 1 or s1). In response to these stimuli, they produced a button press and response times were recorded. For the second task, they were instructed to follow the lead car. When the lead car braked (stimulus for task 2 or s2), participants were instructed to press the brake pedal and braking times were recorded. Three different time intervals (SOAa) between the presentation of s1 and s2 were considered: 300ms, 600ms and 1200ms. Compared to experiments 1 to 4, in this experiment we decided not to consider the shortest, 150ms SOA. We decided to do so because preliminary data showed that with such a short SOA participants tended to maintain a long headway to the lead car, a phenomenon that kept them from having a clear view of the lead car and its brake lights. Each experimental block was composed by a total of 46 trials containing: 16 single-task (8 for t1 and 8 for t2) and 30 dual-task trials (10 trials for each SOA). Before starting the experiment, participants drove two different adaptation scenarios, designed to reduce the likelihood of developing simulator sickness (Draper, Viirre, Furness, & Gawron, 2001). Each of the two scenarios lasted ten minutes. Afterward, the experiment begun. Participants were instructed to follow the lead vehicle and never pass it and to prioritize the first task. Each experimental block lasted for approximately 15 minutes. After each block, participants filled out the edited version of the NASA-TLX. The presentation of the three experimental blocks was counterbalanced across participants and the presentation of trials within blocks were randomized.

Apparatus and stimuli

A PatrolSim high-fidelity driving simulator (L3 Communications/I-SIM), was used. The simulated vehicle is based on the vehicle dynamics of a Crown Victoria model with automatic transmission built by the Ford Motor Company. The simulator consists of three screens providing a front view and two side views to the driver (the horizontal visual field is approximately 180°) and includes rear view and side view mirrors. The sampling rate of the simulator is 60hz. A freeway road simulated a 32-mile multilane highway with on and off ramps, overpasses, and two- and three-lane traffic in each direction. Participants were instructed to follow a lead vehicle according to the car-following paradigm (e.g., Rossi et al., 2012). The lead vehicle travelled in the right-hand lane at a speed of 65 mph. For the first task, participants were presented with either auditory (block 1), vibrotactile (block 2) or multimodal (block 3) stimuli. Auditory stimuli were 75-dB, 2000 Hz pitches presented for 200ms by two speakers located on the dashboard. These stimuli were in accordance with the standards for auditory warnings released by ISO (2013) and SAE (2003). Vibrotactile stimuli, presented for 200ms, had the same characteristics and were presented via the same devices as those used in previous experiments. Multimodal stimuli were auditory and vibrotactile stimuli presented at the exact same time for 200ms. A micro-switch as that used by Strayer et al. (in press) worn by participants on their right hand was pressed in response to the presentation of the stimuli. For the second task, every time the lead car braked, its brake lights went on. An augmented version of the NASA-TLX containing a seventh scale measuring the feeling of urgency associated with auditory, vibrotactile and multimodal stimuli was administrated to participants. The perceived urgency of a stimulus is defined in terms of how strong is the impulse to execute a given action after the presentation of the stimulus (Lewis, Eisert, & Baldwin, 2014) so that the more urgent the signal the stronger the impulse and vice versa. Within the driving context, high urgent warnings are observed to produce benefits only in high emergency situations when, for instance, a collision is about to occur if no corrective maneuvers is executed (Marshall, Lee, & Austria, 2007).

RESULTS

Reaction times

RT were screened for outliers. In particular, reaction times exceeding 2.5 standard deviation (less than 5%) from the mean were removed and not further analyzed.

Single-task RT1 were analyzed by performing repeated measures ANOVAs with stimuli (3 levels: auditory, vibrotactile and multimodal) as within-subject factor. A significant effect of stimuli was found, $F(2, 38)=8.4$, $p<.05$, $p\eta^2=.30$. Pairwise comparisons revealed that multimodal stimuli produced faster responses compared to both auditory and vibrotactile stimuli presented separately ($p<.05$). The same analysis were performed on RT2. No significant differences were found, $F<1$. Dual-task RT1 were analyzed by performing repeated-measure ANOVA with stimuli (3 levels: auditory, vibrotactile and multimodal) and SOA (3 levels: 300ms, 600ms, 1200ms) as within-subject factors. Significant effects of stimuli, F(2, 38)=12.8, $p<.05$, $p\eta^2=.40$, and SOA, F(2, 38)=6.5, $p<.05$, $p\eta^2=.25$, were found. Subsidiary pairwise comparisons revealed that multimodal stimuli produced faster response times compared to both unimodal stimuli ($p<.05$). The same analysis were executed for RT2. We found a significant effect of SOA, F(2,38)=14.9, $p<.05$, $p\eta^2=.44$, but no effect of stimuli and interaction. Reaction times for task 1 and task 2 are showed in table 8.

Modality	**Reaction Times**	
	Task 1	*Task 2*
Auditory	370.40	904.27
Vibrotactile	413.77	859.89
Multimodal	311.45	875.68

Table 8. Reaction times for task 1 and 2 in single-task conditions across sensorial modalities.

Subjective workload

A repeated measure ANOVA with signals (3 levels: auditory, vibrotactile, bimodal) and scales (7 levels: mental, physical, temporal, performance, effort, frustration, urgency) as within subject factors revealed significant effect of scale, F(6, 114)=31.0, $p<.05$, $p\eta^2=.62$ and interaction, F(12, 228)=1.8, $p<.05$, $p\eta^2=.09$. Further repeated measure ANOVA with signals (3 levels: auditory, vibrotactile, bimodal) were executed for each of the seven scale constituting the NASA-TLX. The only scale showing differences across signals is the perceived urgency scale, F(2, 38)=5.3, $p<.05$, $p\eta^2=.21$. Subsidiary comparisons showed that the level of perceived urgency for bimodal signals (M=11.85) was significantly higher compared to that of both auditory (M=9.75), t(19)=3.12, $p<.05$, and vibrotactile (M=10.2), t(19)=2.4, $p<.05$, signals.

DISCUSSION

The findings obtained in experiment 4 for task 1 were replicated with participants driving a simulated vehicle. In particular, when presented with multimodal stimuli, drivers executed faster responses compared to when auditory and vibrotactile stimuli were presented separately. This finding is of the utmost importance for a number of reasons. First, it shows that the redundancy gain found in the previous in-lab experiments may even be observed within applied contexts such as driving. Second, it suggests than employing multimodal stimuli as warnings may reduce drivers’ response times in a more naturalistic condition with them driving a vehicle equipped with ADAS. Because of that, multimodal warnings are likely to have a significant, positive impact on road safety, speeding up drivers’ reaction when the driving conditions become dangerous and, therefore, when prompt driving adjustments are therefore needed.

About task 2, results show that the facilitation found for rt1 with multimodal stimuli does not propagate onto rt2. Unlike in experiment 4, no significant difference was indeed observed for rt2 across sensorial modalities. This is likely due to the fact that in this experiment, executing an actual braking task required a larger amount of resources compared to experiment 4 in which participants performed a surrogate braking task. Such a difference, resulting in a large increase in rt2 (900ms in exp.5 vs. 500ms in exp.4), may likely have eliminated the benefit (ranging from 60 to 100ms) associated with multimodal stimuli found for rt1.

2.4 Conclusions

By considering the psychological refractory period as paradigm, we aimed to measure the interference produced by the processing of a number of stimuli (task 1) on the execution of a secondary, braking task. Visual warnings were observed to produce the largest interference on task 2. This is not surprising considering that, for the second task, participants pressed a pedal in response to the presentation of a visual stimulus. This datum is in agreement with cross-talk theories (Navon & Miller, 1987) and, within a more applied context, with the multiple resource theories by Wickens (2008) and the model of driving distraction of Strayer, Watson and Drews (2011). Further, auditory and vibrotactile warnings were observed to produce a less degree of interference with vibrotactile warnings, in particular, producing faster responses than auditory – 368ms vs. 411ms. Interestingly, a speed-accuracy trade-off was not observed but, for what concerns subjective workload, a reduced mental workload and effort was found for auditory stimuli when compared to both vibrotactile and visual stimuli. A fourth experiment considering multimodal warnings was then executed. When vibrotactile and auditory warnings were presented concurrently (AND condition), a multisensory response enhancement ranging from 40% to 60% depending on the SOA was found. This suggests that, compared to the situations in which these warnings are presented separately (OR condition), response times in the multimodal condition were 40% to 60% faster. Such an enhancement was found to reduce the dual-task interference to only 77ms. Moreover, no speed-accuracy trade-off was found for multimodal warnings but, interestingly, a reduction in error rate was observed. This suggests that the benefit of presenting multimodal warnings is not limited to response times but it extends to accuracy as well.

The data obtained in these five experiments serve as an empirical base for additional studies in which the effects produced by the presentations of different types of warnings are investigated within a more naturalistic context with participants driving a simulated vehicle equipped with an advanced assistance system. It is indeed possible that, because we considered the PRP as paradigm with participants executing button presses for t1 (a somewhat unusual response for the driving context), the data we obtained in experiment 5 may not be fully replicated when driving in a more realistic situation.

Our study is of importance for the driving research. Different sensorial modalities and, therefore, warnings produce different levels of performance and are associated with different levels of mental workload. Thus it is indeed plausible that well-tailored warnings may be adopted depending on the urgency of the message to be conveyed to the driver. In a critical situation in which a prompt response by the driver is needed, a multimodal warning may represent the most appropriate warning compared to other situations in which a less urgent response is needed (Marshall et al., 2007).

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3 Multimodal, redundant warnings

Presenting multimodal, redundant stimuli speeds up response times and produces a significant increase in the level of perceived urgency. Although these findings were obtained in a driving simulator experiment, two are the main limitation of experiment 5. First, participants were not presented with warnings but with stimuli associated with no specific significate. Second, in response to these stimuli, they executed button presses, a behavior quite uncommon for the driving context. For such reasons, a more thorough investigations of the effects of multimodal warnings on drivers' behavior within a more naturalistic environment is needed.

3.1 Experiment 6

As discussed previously, advanced assistance systems may have a positive impact on road safety and reduce accidents by 20% (House of Commons, 2004). On the other hand, talking on a cell phone while driving has been widely evidenced to impair driving behavior by, for instance, slowing braking times (Rossi, Gastaldi, Biondi, & Mulatti, 2012; see, Caird, Willness, Steel, & Scialfa, 2008 for a review). In order to reduce the negative impact of distraction on road safety, car-manufacturers are developing a number of collision avoidance systems. The rear-end collision avoidance system (NHTSA, 2006), for instance, constantly monitors the distance to the lead vehicle and, if the distance is too short, warnings are presented. In response to these warnings, drivers are usually required to execute fast braking responses.

This experiment has two main aims. First, we investigate whether multimodal warnings emitted by a rear-end collision avoidance system are capable of speeding up drivers' braking times. Second, if benefits associated with multimodal warnings are found, we are interested in observing whether such benefits may be replicated with drivers being distracted by a concurrent cell phone conversation.

METHOD

Participants

Twenty-two undergraduate students (fourteen females) at the University of Utah participated in this experiment. They had an average age of 25 years (standard deviation = 6 years) and possessed a valid driver license for an average of 9 years (standard deviation = 6 years). They had normal or corrected-to-normal vision, did not use cochlear implants or any other hearing device and did not report having hearing deficits. One participant dropped out due to simulator discomfort.

Design

We employed a four by two within subjects factorial design. The first factor was the kind of warning. In particular, we had four different warning conditions: 1-control (no warnings), 2-auditory warnings, 3- vibrotactile warnings, 4- multimodal warnings (vibrotactile and auditory signals were presented concurrently). The second factor was the cellphone use. In the first condition, participants were driving and responding to warnings and in the second, in addition to that, they were instructed to carry on a conversation over a hands-free cellphone with one of their friends/acquaintances. The order of conditions was randomized across participants.

Materials

A PatrolSim high-fidelity, fixed base driving simulator (L3 Communications/I-SIM), was used. The simulated vehicle is based on the vehicle dynamics of a Crown Victoria model with automatic transmission built by the Ford Motor Company. The simulator consists of three screens providing a front view and two side views to the driver (the horizontal visual field is approximately 180°) and includes rear view and side view mirrors. The sampling rate of the simulator is 60hz. A freeway road simulated a 32-mile multilane highway with on and off ramps, overpasses, and two- and three-lane traffic in each direction. The simulated vehicle driven by participants was equipped with a rear-end collision avoidance system. This assistance system constantly monitored the time-to-collision (Lee, 1976). Participants were instructed to follow a lead vehicle according to the car-following paradigm (Brackstone & McDonald, 1999; Ciuffo, Punzo, & Montanino, 2012; Gipps, 1981). The lead vehicle travelled in the right-hand lane at a speed of 65 mph and it was programmed to brake for a total of eight times during each drive (see the procedure for a more detailed description of the braking events). The auditory warning was a 75-dB, 2000 Hz auditory stimulus presented by two speakers located on the dashboard. The auditory warning was in accordance with standards released by *ISO (2013*) and *SAE (2003).* The vibrotactile warnings had an amplitude of 0.5 G and were delivered by two LilyPad© Vibe motors each of those located on one of the driver's hand palm. The motors were connected to the pc running the simulation via an Arduino© Uno microprocessor, programmed with the assistance of Joel Cooper, Ph.D. (Precision Driving Research, Salt Lake City, Utah). Auditory and vibrotactile warnings - presented either separately or together - were presented for 200ms every second (200ms followed by 800ms of silence) until a braking response by drivers was detected. All participants correctly detected the warnings. Drivers' subjective workload was measured by using an augmented version of the NASA-TLX (Hart & Staveland, 1998). When participants were talking on a hands-free cellphone, we used an IPhone 6© (Apple© Inc.) connected to a model Era Bluetooth earpiece manufactured by Jawbone©. The cellular service was provided by Sprint©.

Procedure and instructions

Before starting the experiment, participants drove two different adaptation scenarios, designed to reduce the likelihood of developing simulator sickness (Draper, Viirre, Furness, & Gawron, 2001). Each of the two scenarios lasted ten minutes. Afterward, the experiment begun. Participants were instructed to follow the lead vehicle and never pass it. In each of the eight experimental conditions, the lead vehicle was programmed to brake a total of eight times. We created eight different scenarios, one per experimental condition; in each scenario, the brake events were programmed to occur at specific road sections, always different across scenarios. For these reasons, the road sections at which the lead car braked were highly unpredictable to participants. Whenever the lead vehicle braked, it decreased its speed from 65mph to 30mph and if participants did not brake as a consequence, the lead vehicle could reach a complete stop. In order to avoid any confounding effects associated with the onset of braking lights, the lead vehicle's braking lights were disabled. Such a procedure, adopted in a number of other studies (e.g., Ho, Reed, & Spence, 2006; Mohebbi et al., 2009), was considered to resemble all those situations in which the driver is not looking at the lead vehicle as a consequence of, for instance, being distracted looking at the onboard computer display or other vehicles on the roadway. In this type of situations, if the lead vehicle brakes, the driver must therefore rely on the information provided by assistance systems. Every time the lead vehicle braked and the time-to-collision was shorter than five seconds (Mohebbi et al., 2009; Scott & Gray, 2008), warnings were presented to inform the drivers that they had to brake in order to avoid a collision. Warnings were presented until the time-to-collision was larger than five seconds or a collision occurred. In the case of a collision, a collision message appeared on the central of the three monitors and the simulation stopped. Whenever a collision occurred that particular experimental drive was considered concluded and the next drive started. In the auditory warning condition, auditory warnings were presented to drivers. In the vibrotactile warning condition, vibrotactile warnings were presented to drivers. In the multimodal warning condition, auditory and vibrotactile warnings were presented to drivers at exactly the same time. In the no-warning/control condition, no warning was presented to drivers. In total, participants drove eight experimental drives, each of them lasting for about five minutes. Halfway through the experiment, lasting approximately one hour, participants took a 15-minutes break. After each and every drive, participants were administrated the NASA-TLX and they had to respond to the questions contained in it. The order in which participants drove the eight experimental drives was randomized across participants.

Dependent measures

The main dependent measure we considered was Braking Reaction Times (BRT). As discussed in the procedure section, the lead car was programmed to brake a total of eight times and drivers, in response to that, were instructed to brake. We defined T_0 as the time point at which, after the lead car brakes, the TTC between the vehicles was less than 5 seconds. Similarly, we defined T_1 as the time point at which the driver initiated the braking response by pressing the brake pedal. BRT are therefore calculated as the difference in seconds between T_1 and T_0. BRT are calculated in the same manner in both the control/no-warning and the warnings conditions. The only difference is that, in the latters, warnings are presented at T_0. Our second dependent measure was the subjective workload measured via an augmented version of the NASA-TLX (Hart & Staveland, 1988). As in experiment 5, in addition to the six scales constituting the original questionnaire, we added the urgency scale (Lewis, Eisert, & Baldwin, 2014).

RESULTS AND DISCUSSION

Repeated measure ANOVAs will be conducted to analyze BRT and NASA-TLX data. The Greenhouse-Geisser correction will be considered. For post-hoc comparisons, the Bonferroni correction will be adopted; the corrected alpha is obtained by dividing the .05 alpha by the number of comparisons executed.

BRT

A 2 cellphone (no cellphone, cellphone) x 4 warnings (no-warning, auditory, vibrotactile, multimodal) repeated measures analysis of variance (ANOVA) performed on the data revealed significant main effects of cellphone, $F(1,21) = 20.01$, $p<.05$, partial $\eta^2 =.48$, and warnings, $F(3,63) = 134.41$, $p<.05$, partial $\eta^2 =.86$. BRT were found to be slower in the cellphone compared to the no-cellphone condition (see figure 1). The interaction was not significant. Subsidiary pairwise comparisons revealed that reaction times in the no-warning condition (M=1.66s and M=1.89s in, respectively, the no-cellphone and cellphone conditions) were longer compared to those recorded in all of the other experimental conditions ($p<.008$). Interestingly, reaction times to redundant, multimodal warnings (M= 0.59s and M= 0.66s in, respectively, the no-cellphone and cellphone conditions) were faster compared to auditory (M=0.72s and M=0.89s in, respectively, the no-cellphone and cellphone conditions; ps<.008) and vibrotactile (M=0.80 s and M= 0.97s in, respectively, the no-cellphone and cellphone conditions; ps<.008) warnings regardless of whether participants were talking on the phone or not. BRT for auditory warnings were not significantly different to those recorded with vibrotactile warnings ($p>.008$). In addition, in the cellphone condition, BRT for auditory warnings were faster compared to those recorded with no-warnings ($p<.008$), a result different to that obtained in the study of Mohebbi et al. (2009) in which participants, instead of talking on the cellphone, were executing a cognitive task requiring a larger amount of attentional resources. About multimodal warnings, BRT in the cellphone condition were significantly longer than those in the no-cellphone condition. BRT are shown in figure 1.

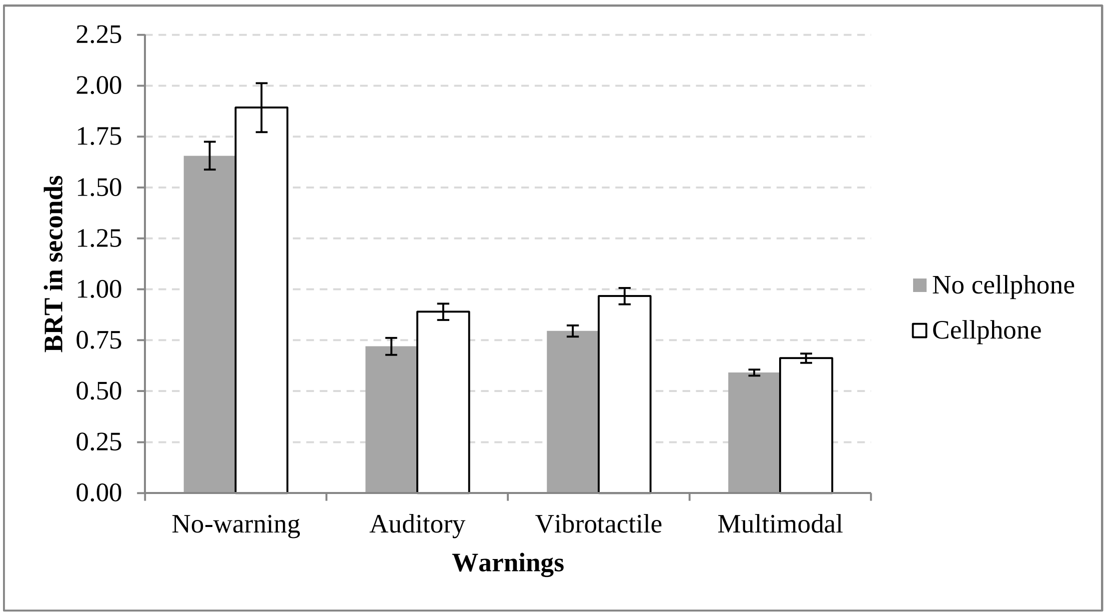

Figure 1. Mean braking reaction times and standard error (SE) in seconds across warnings and cellphone conditions.

The findings we obtained in this experiment are of the primary importance for a number of reasons. First, multimodal, redundant warnings were observed to produce faster responses by drivers when compared to unimodal (i.e. either vibrotactile or auditory) warnings. This represents one of the first studies in which the benefits associated with the redundant target effect were observed within the driving context. Second, we observed that the benefit associated with multimodal warnings occurs regardless of whether participants were engaged in a conversation or not. These results therefore suggest that presenting multimodal warnings has a positive effect on driving even when drivers are distracted and their response times are usually prolonged (Rossi et al., 2012). Compared to the auditory and vibrotactile warnings conditions, in the multimodal condition we observed a reduction in braking times up to 300ms. Such a benefit may likely reduce the likelihood of collisions and, as a consequence, increase road safety for two main reasons. First, according to the National Highway Traffic Safety Administration (NHTSA, 2013) rear-end collisions account for 28% of the total number of on-road crashes and it is estimated that assistance system may reduce the occurrence of this type of collisions by 40% - therefore, a system capable of warning the drivers more quickly should impact positively on these estimates. Second, in our experiment, warnings were presented to drivers only when the time-to-collision was shorter than five seconds. This suggests that employing multimodal warnings may reduce braking times by significant percentages: 6% of the total time (5 seconds) available to them before a collision occurred and 30% compared to other warnings. Interestingly, however, no warning x cellphone interaction was found. This suggests that the presentation of multimodal warnings is not able to circumvent the bottleneck associated with talking on a cellphone; likely because our manipulation affected an earlier stage of processing – we will return later on this issue.

NASA-TLX

A repeated measure ANOVA with cellphone (2 levels), warnings (4 levels: no-warning, auditory, vibrotactile and multimodal) and scale (6 levels: scales 1 to 6 of the NASA-TLX) as within-subject factors was conducted. Since the urgency scale was not administrated in the no-warning condition, urgency data will be analyzed in a separate ANOVA. Significant effects of warnings, $F(3,57) = 16.47$, $p<.05$, partial $\eta^2 =.46$, scale, $F(5,105) = 122.70$, $p<.05$, partial $\eta^2 =.86$, and cellphone x scale interaction, $F(5,105) = 11.55$, $p<.05$, partial $\eta^2 =.37$, were found. No main effect of cellphone was found. Pairwise comparisons using the Bonferroni correction were conducted to investigate differences across warnings. The overall subjective workload measured in the no-warning condition was significantly lower compared to those measured with warnings ($p<.001$); no significant differences were found between auditory, vibrotactile and multimodal warnings. Two separate repeated-measures ANOVAs were conducted to investigate differences across warnings for the annoyance and urgency scales (respectively, scale 6 and 7 of the augmented NASA-TLX). Given the relevance of annoyance and perceived urgency for warnings, we decided to focus on these two scales. For annoyance, two within-subject factors were considered: cellphone (2 levels) and warnings (4 levels); for urgency, in addition to cellphone, the second factor was warnings having, in this case, 3 levels (the urgency scale was not administrated in the no-warning condition). For the annoyance scale, a significant main effect of warning, $F(3,63) = 6.73$, $p<.05$, partial $\eta^2 =.26$, was found. Pairwise comparisons with the Bonferroni correction reveled that, although the multimodal warning condition produced a higher feeling of annoyance compared to the no-warning condition (M=3.0) ($p<.008$), no differences between auditory (M=4.3), vibrotactile (M=4.3) and multimodal (M=4.5) warnings were found (ps>.008). For the urgency scale, a significant main effect of warning, $F(2,42) = 16.21$, $p<.05$, partial $\eta^2 =.46$, was found; pairwise comparisons with the Bonferroni correction found significant differences with auditory (M=8.2) and multimodal (M=9.7) warnings producing higher feelings of urgency compared to vibrotactile warnings (M=6.7)(ps<.008).

Compared to unimodal auditory and vibrotactile warnings, multimodal warnings are not associated with an increase in the level of annoyance. About perceived urgency, multimodal and auditory warnings produced a higher feeling of urgency compared to vibrotactile warnings. For this reason, we suggest that employing multimodal warnings, given the benefit in terms of braking times associated with them, may be more appropriate in high-emergency situations in which fast, prompts corrective maneuvers are needed.

3.2 Experiment 7

Although talking on a cellphone is associated with a large speed variability (Cooper, Vladisavljevic, Medeiros-Ward, Martin, & Strayer, 2009), which likely is a determining factor for rear-end collisions, most rear-end collisions occur in urban areas (NHTSA, 2007) where, among other things, traffic is usually more dense than in rural areas. In our second experiment we want to investigate whether presenting multimodal, redundant warnings may still be effective while driving in high-density traffic conditions.

METHOD

Participants

Twenty-two undergraduate students (sixteen females) at the University of Utah participated in this experiment. They had an average age of 27 years (standard deviation=8.9 years) and possessed a valid driver license for an average of 10 years (standard deviation=8.7 years).

They had normal or corrected-to-normal vision, did not use cochlear implants or any other hearing device and did not report having hearing deficits. No one from this sample participated in experiment 1. One participant dropped out due to simulator discomfort.

Design and materials

We employed a four by two within subjects factorial design. As in the first experiment, we had four different warning condition: 1-control (no warnings), 2- auditory warnings, 3- vibrotactile warnings, 4- multimodal warnings (auditory + vibrotactile). The second factor was the traffic density.

Driving simulator, warnings, and lead vehicle's behavior were the same as those of the first experiment .

Procedure and instructions

The procedure and instructions were the same as those considered in experiment 1. In the low-traffic density condition, only the lead vehicle and that driven by participants were on the road. In the high-density traffic condition, other vehicles programmed to drive in the left lane between 5% and 10% faster than the lead vehicle, providing the impression of a steady flow of traffic. Such a manipulation of traffic density was found to be effective in the study by Strayer, Drews and Johnston (2003). As in the previous experiment, we considered two main dependent measures: BRT and subjective workload (adjusted NASA-TLX).

RESULTS AND DISCUSSION

Multiple repeated measure ANOVA will be conducted to analyze BRT and NASA-TLX data. The Greenhouse-Geisser correction will be considered.For post-hoc comparisons, the Bonferroni correction will be adopted; the corrected alpha is obtained by dividing the .05 alpha by the number of comparisons executed.

BRT

A 2 traffic (high vs. low density) x 4 warnings (no-warning, auditory, vibrotactile, multimodal) repeated measures analysis of variance (ANOVA) performed on the data revealed significant main effects of traffic, $F(1,21) = 22.67$, $p<.05$, partial $\eta^2 =.52$, warnings,

$F(3,63) = 122.38$, $p<.05$, partial $\eta^2 =.85$ and a significant interaction, $F(3,63) = 4.73$, $p<.05$, partial $\eta^2 =.18$. BRT were found to be slower in high-density traffic conditions compared to low-density conditions ($p<.05$). Subsidiary pairwise comparisons revealed that in the no-warning condition (M=1.49s and M=1.72s in, respectively, the low- and high- density traffic conditions) braking times were slower compared to the warning conditions ($p<.008$). Presenting multimodal, redundant warnings (M=0.57s and M=0.57s in, respectively, the low- and high- density traffic conditions) produced faster responses compared to when auditory (M=0.64s and M=0.81s in, respectively, the low- and high- density traffic conditions; ps<.008) and vibrotactile (M=0.72s and M=0.90s in, respectively, the low- and high- density traffic conditions; ps<.008) warnings were presented separately. As in the previous experiment, BRT for auditory warnings did not differ from those for vibrotactile warnings ($p>.008$). Interestingly, with multimodal warnings, BRT in the high-density traffic condition were not significantly different to those in the low-density traffic condition($p=.86$). BRT are shown in figure 2.

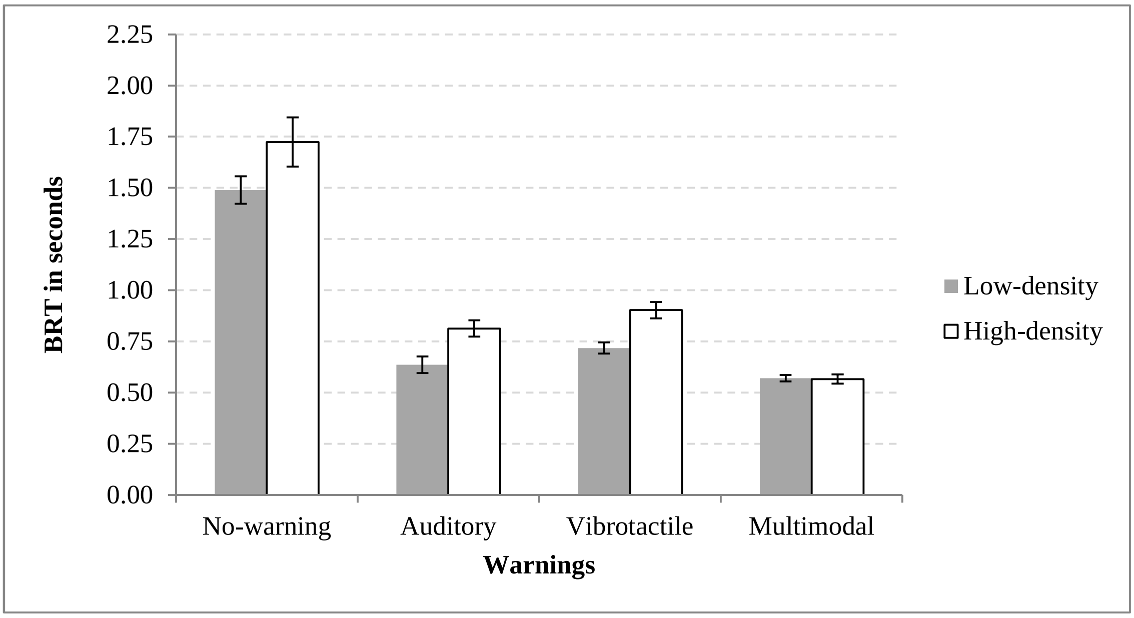

Figure 2. Mean braking reaction times and standard error (SE) in seconds across warnings and high vs. low density traffic conditions.

These results suggest that drivers and, as a consequence, road safety may well benefit from using multimodal warnings when traffic is more dense. Our data indeed show that presenting multimodal warnings in high-density traffic conditions produce faster braking responses compared to when vibrotactile and auditory warnings are presented separately. Further, multimodal warnings were observed to be as effective in high-density traffic condition as they were when traffic was less dense. No significant differences were indeed found for multimodal warnings in the two traffic conditions. Compared to auditory and vibrotactile warnings, drivers were respectively 70ms and 150ms faster with less dense traffic and 250ms and 340ms with high dense traffic. We will return on this issue in the Discussion.

NASA-TLX

A repeated measure ANOVA with traffic (2 levels), warnings (4 levels: no-warning, auditory, vibrotactile and multimodal) and scale (6 levels: scales 1 to 6 of the NASA-TLX) as within-subject factors was conducted. Since the urgency scale was not administrated in the no-warning condition, urgency data will be analyzed in a separate ANOVA. Significant effects of traffic, $F(1,21) = 4.99$, $p<.05$, partial $\eta^2 =.19$, scale, $F(5,105) = 87.17$, $p<.05$, partial $\eta^2 =.80$, and traffic x scale interaction, $F(5,105) = 5.36$, $p<.05$, partial $\eta^2 =.20$, were found. Interestingly, no significant effect of warnings was observed ($p=.078$). Pairwise comparisons using the Bonferroni correction were conducted to investigate further differences. The overall subjective workload measured with high-density traffic was higher compared to that measured with low-density traffic ($p<.001$). Motivated by the findings about the findings obtained in experiment 1, separate ANOVAs were conducted to investigate differences for the annoyance and urgency scales. A repeated measure ANOVA with traffic (2 levels) and warnings (4 levels) as within-subject factors conducted for the annoyance scale revealed no significant effect of warnings, $F(3,63) = 1.5$, $p=.22$, partial $\eta^2 =.06$. A similar analysis performed for the urgency scale with traffic (2 levels) and warnings (3 levels: auditory, vibrotactile and multimodal) as within-subject factors revealed a significant effect of warnings, $F(2,42) = 4.1$, $p<.05$, partial $\eta^2 =.16$. Pairwise comparisons with the Bonferroni correction revealed significant differences with multimodal warnings ($M=9.2$) producing a higher feeling of urgency compared to vibrotactile warnings ($M=7.2$) ($p<.008$); no significant differences were found between vibrotactile and auditory warnings ($M=8.2$) ($p>.008$).

In this experiment we found similar patterns of results compared to those of the previous experiment. In particular, multimodal warnings produced no significant increases in annoyance compared to the other three conditions. About perceived urgency, multimodal warnings were found to produce a higher feeling of urgency compared to vibrotactile warnings.

3.3 General Discussion

Presenting multimodal, redundant warnings produces fast, prompt brakes by drivers. Compared to when auditory and vibrotactile warnings are presented separately, presenting these warnings concurrently produces significant reductions in response times, up to 340ms in our second experiment. This finding is of the utmost importance if we recall that in our experiments warnings were presented when an imminent collision was about to occur. Moreover, subjective workload ratings showed that responding to multimodal warnings is not associated with a more elevate feeling of annoyance (measured via the sixth scale of the NASA-TLX) when compared to vibrotactile and auditory warnings This suggests that the reduction in braking times observed with multimodal warnings and its consequent benefit for road safety do not trade-off with a larger feeling of irritation or discomfort, aspects that may determine whether an assistance system will be used or, more drastically, switched off (Jamson, Lay, & Carsten, 2008)

Multimodal, redundant warnings were found to be effective even when drivers were distracted and the traffic was dense. Interesting, however, is the fact that while the multimodal warnings eliminated the cost associated to driving in a dense traffic environment (Experiment 7), the same phenomenon was not observed with participants talking on a cellphone (Experiment 6). An explanation of this pattern of results may be found in the three sources of distraction theory of Strayer, Watson and Drews (2011). Talking on a cellphone, especially if, as in our case, the device is hands-free, represents, in the main, a cognitive task. Individuals have to listen to the message produced by the other speaker, understand it, process an adequate response and, only at last, produce a motor response (Mulatti, Lotto, Peressotti, & Job, 2010). Although the final stage involves motor activation, the core of the task is cognitive (Rossi et al., 2012). Driving in the traffic, on the other hand, is also associated with a significant amount of low-level, visual distraction. Indeed, while in the traffic, drivers have to move their eyes off the road and, because of that, they may get distracted by just looking at other vehicles. As seen in experiment 4, although using multimodal, redundant stimuli for the first task reduced the dual-task cost (Pashler, 1994) produced by executing these two tasks concurrently, these stimuli were never able to completely eliminate it. We interpreted these data by concluding that, within a dual-task context, presenting multimodal, redundant stimuli may have a facilitatory effect at the perceptual stage of processing but not at the cognitive, given that the cost was never eliminated. From this perspective, the results obtained in the sixth experiment may be accounted for as a consequence of the inability of multimodal, redundant warnings to circumvent the bottleneck associated with the execution of the cognitive demanding cellphone task. On the other hand, since a large part of the load associated with driving in the traffic is visual, presenting multimodal warnings may have successfully broken through the perceptual component of the dual-task cost in the seventh experiment - an hypothesis in accordance with multiple resource theories (Wickens, 2008).

Talking on a cellphone has been widely observed to slow braking times (e.g., Strayer & Drews, 2004) and, as a consequence, increase the likelihood of getting into accidents (e.g., Redelmeier & Tibshirani, 1997) especially when traffic is congested. The findings we obtained in our experiments are of importance for car manufacturers. Since multimodal warnings produced an elevate feeling of urgency, we suggest that the benefit associated with these warnings may be maximized in high emergency situations when a severe collision is about to occur if no appropriate maneuver is executed.

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4 Multimodal warnings .. what then?

Multimodal, redundant warnings speed up drivers' responses and produce an elevate feeling of urgency. In this conclusive chapter I will focus on what these warnings will be useful for and provide a few ideas about further studies needed to effectively implement these warnings in the automobile.

4.1 The driver's status

In order to be successfully implemented in the automobile, ADAS and warnings must be capable of capturing drivers' attention and effectively inform them about the upcoming hazards across different levels of, e.g., traffic, distraction and fatigue. In experiments 6 and 7, I addressed two of these issues by having participants talking on the cell phone and driving in dense traffic. However, many are the aspects in association with ADAS and multimodal warnings needing further investigation. Here I will discuss a few of them.

Older drivers. With the general population ageing, older drivers constitute a growing portion of the driver population. A 23% increase of older drivers was indeed observed in the 1999-2009 decade (CDC, 2014). Ageing is associated with specific reductions in cognitive and motor functioning that, applied to driving, are often found to slow braking responses (e.g., Summala, 2000) and impair scanning behavior (e.g., Romoser, 2012). In order to be adopted, multimodal warnings presented by ADAS must be effective even with an older driver at the wheel of the car. It is indeed possible that older drivers would show different responses to the presentation of multimodal warnings compared to those executed by the young drivers in experiments 6 and 7. Further research toward measuring the effect of age on drivers' response to (multimodal) warnings is therefore necessary to design tailored warnings, effective across different age groups.

Fatigue. Fatigue and drowsiness are estimated to be the cause of around 100 thousand crashes per year in the United States only (NHTSA, 2014). May and Baldwin (2009) distinguish between three different types of fatigue: active task-related fatigue, passive task-related fatigue and sleep-related fatigue. Sleep-related fatigue is closely related to sleep deprivation, circadian rhythms and the time of the day in which the driving task is performed. Two times of the day with drivers being usually drowsy are, for instance, the early morning and the early afternoon – a phenomenon known as post-lunch dip (Lennè, Triggs, & Redman, 1997). During these intervals, drivers' braking times and speed control are usually worse compared to other times of the day. Nonetheless, few are the studies investigating the effects of warnings on drowsy drivers (e.g., Kozak et al., 2006). For this reason, further research is needed in order to observe whether and how multimodal warnings may be beneficial even in sleep-related fatigue conditions.

Emergency. Multimodal warnings were found to produce an elevate feeling of urgency (Baldwin, & Lewis, 2013). For this reason, high emergency conditions requiring, for instance, fast braking responses may represent the most appropriate situations in which to employ multimodal warnings. About other driving situations associated with different levels of emergency, it is not clear yet which may be the most suitable warnings. It is indeed likely that the responses to multimodal warnings observed in previous experiments may not be appropriate in other driving contexts requiring, for instance, a slower, more accurate swerving maneuver. Further research is therefore needed in order to create tailored warnings being effective as the level of emergency and the type of response required change.

4.2 Automated vehicles

Automated vehicles represent the present and future of transportation. Automated vehicles are those in which a number of driving functions is delegated to the automated system. Many are the entities being interested in automated vehicles; among these, car-manufacturers and governmental institutions. In 2013, the National Highway Traffic Safety Administration released a document containing a classification of different levels of automation in vehicles (NHTSA, 2013). Depending on the number of driving operations being assigned to the system and the types of conditions in which the system is capable of taking control of the vehicle, we can distinguish between combined-function automation (level 2 of 4), limited self-driving automation (level 3 of 4) and full self-driving automation (level 4 of 4). One of the main research issues related to self-driving vehicles (level 4) concern unexpected transitions from automated to manual drive (Biondi, Strayer and Drews, 2014). Unlike with level 3 vehicles, with self-driving vehicles the driver in not supposed to monitor any of the driving processes at any time. For such a reason, if at some point a system failure occurs and the driver is required to take over the vehicle, if s/he is occupied doing something else, the transition may end up with tragic consequences.

The findings presented in my dissertation may well be applied to self-driving vehicles. In the instance described above, presenting multimodal warnings during such a critical transition may indeed capture the attention of the driver and lead him/her back to be in full control of the driving task.

4.3 Final remarks

After executing the seven experiments contained in this dissertation and discussing the more relevant findings, I have provided the reader with a few ideas of future researches and areas in which employing multimodal warnings. Many more, however, are the applications of multimodal warnings within the driving field and, further, other contexts such as the navigation of visually impaired people (Henze, Heuten, & Boll, 2006) and emergency and operating rooms in hospitals (Shmid et al., 2011).

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