Perceptual influence of the vibratory component on the audio component of alarms produced by rumble strips, by measuring reaction times

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The aim of the ROADSENSE ANR-10-VPTT-010-01 project is to define a driver assistance that prevents involuntary lane departure. Soon as one drives over an audio-tactile lane-marking (ATLM), it produces a vibratory and sound alarm that helps the driver getting back on the road. Based on an objective measurement using simple reaction time, the perceptual influence of the vibratory component on the audio component of alarms produced by ATLM was studied. Two situations were compared: the first one with sound only and the second one with sound and vibration. During this experiment, participants were placed in a semi-realistic driving situation and were asked to press a pedal as soon as possible when they perceived an alarm. Audio-vibration alarms were synthesized by extracting a signal pattern from real recordings of sound and vibrations produced by ATLM. This pattern (vibration and sound) was repeated using three different inter onset intervals (IOI). Values of reaction times show neither an effect nor an interaction of the vibration component on the audio component of the alarm. However, the influence of the IOI is important; shorter is the IOI, better is the reaction time. This result is in agreement with previous results from the literature.

1 Introduction

1.1 The Roadsense project

The goal of the ANR Roadsense is to alert effectively drivers leaving inadvertently the traffic lane in order to cause a fast reaction for coming back on the roadway. This alert is produced by an audio-tactile lane-marking (ATLM) on the middle or on the edge of the road.

Depending on the country, ATLM are designed in different manners including: raised, milled-in, rolled-in rumble strips, or spots, see Figure 1.

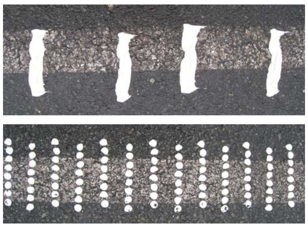

Figure 1: Different types of ATLM located on French roads (Top: raised, bottom: spots).

When a vehicle crosses those delineations, ATLM produced a bimodal signal, i.e. a sound and vibration signal, with the function to warm up the driver [1]. One goal of the Roadsense project is to design efficient ATLM to alert as fast as possible drivers by means of the signal's sound component.

To reach this goal it is required to reveal the sound component's physical parameters producing the fastest reaction of a driver leaving the lane. In the present study, the effect of physical parameters is evaluated using a simple reaction time paradigm. In this paradigm, participants have to react, by pushing a button for example, as fast as possible when detecting a signal. In the framework of the Roadsense project, the goal is thus to reveal the sound component's physical parameters with greater effect on reaction time in order to design efficient ATLM. However, as it was mentioned before, an ATLM produces a bimodal signal composed of a vibratory component and a sound component. So the first question, on which the present article focuses, is to examine whether the vibratory component may interact with the sound component? In other words, are the effects of both components independent? If this statement is true, the design of the sound component of the ATLM could be thought independently of the vibratory component.

In a previous study, it was shown using a driving simulator that vibrations have a weak influence on the annoyance judgments of sound inside the vehicle in bimodal presentation of the stimuli: a car seat excited in vertical direction combined with a vibrating steering wheel and the noise car engine [2]. In a different study about in-vehicle lane departure warning systems, Stanley [3] measured reaction times (time to return to lane) to different warnings. Warnings were provided by unimodal stimuli like audio warnings (pre-recorded "rumble strips") or haptic warnings through a vibrating seat or bimodal presentation including both warnings. Results showed that the unimodal haptic condition reduced significantly the reaction times (time to return to lane) [3]. Even if these experiments involved different tasks (annoyance judgments and objective measures of urgency), these results indicate that the perceptual influence of a sound component and a vibratory component can't be generalized, depending on the experimental context. In the current study, the perceptual influence of the vibratory component on the sound component of alarms produced by rumble strips are examined, by measuring reaction times using two experimental conditions: unimodal condition (auditory warning) and bimodal condition (auditory and vibratory warnings).

In the next section, literature on audio warnings and urgency will be first presented. Based on this overview, guidelines for the elaboration of the stimuli will be provided. Then, the experimental setup, using a driving simulator with a vibrating steering wheel, and the experimental procedure, using reaction time measurement, will be presented. Finally, results will be discussed.

2 Auditory warnings and urgency

When driving, some situations require to communicate urgency information in order to react quickly. Studies have shown that communicating information with non-speech sounds benefits from an accurate temporal resolution of the hearing system and also reduces demands on visual attention [4]. Mainly, three different types of sounds are used to convey information: auditory icons (natural or everyday sounds), earcons (abstract sounds) and speech sounds [5]. These different types have been used in contexts like operating rooms, driving simulators, cockpits, etc., where urgency information (degree of urgency and nature of the urgency [6]) is vital to convey. For example a study [7] showed that a "corn horn" sound or a semantic verbal sound played to attract the driver's attention when a car approaches at high speed from behind.

The ATLM are physical repeated patterns that produce sound and vibration whenever the wheels of a vehicle cross them (Figure 1). The period corresponds to the fixed distance between contiguous ATLM. Generally this physical period gives the fundamental frequency of the warning signal (sound and vibration). In this context, the sound production is comparable to the framework proposed by Patterson [8] [6] to design alarm sounds, Figure 2.

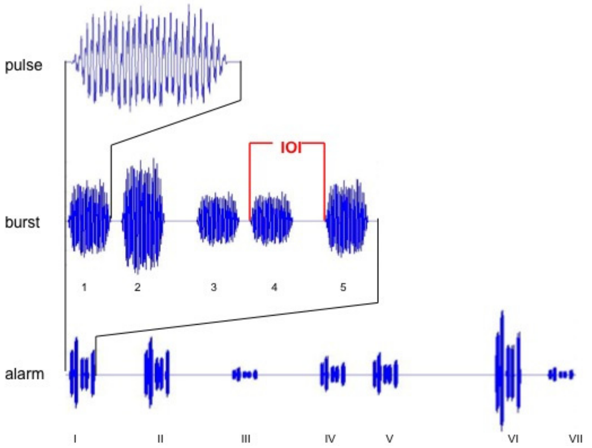

Figure 2: The three steps to build an auditory warning, pulse, burst and alarm. IOI is the inter onset interval.,

First, a sound alarm should be audible, but not too loud; Patterson [8] recommends that at least four spectral components emerge 15 dB above the auditory threshold for each component. Then, an alarm can be designed in three successive steps. At first, a pulse is synthesized. This pulse has its proper characteristics (fundamental frequency, harmonic or not, temporal envelop, off and on set). In a second step, a burst is constructed as a sequence of alternating pulses (with different characteristics or not) and periods of silence. The inter onset interval (IOI) is the time including a pulse and a following silent period (see Figure 2). An alarm is composed by different bursts. Based on this structure, the modification of parameters (pulse, burst) conveys different levels of perceived urgency. Different authors [9] [10] have tested experimentally, using subjective measures, how urgency perception was modified when changing different acoustical parameters of an alarm's pulses and the bursts. They found that the IOI parameter is the most suitable to convey urgency information, followed by the number of pulse repetitions, the burst's fundamental frequency, and irregularity of harmonic content. Guillaume et al. [11] showed that cognitive process affects the influence of acoustical parameters on perceived urgency.

3 Experiments

In the case of a driving situation, ATLMs alert the drivers deviating from their lanes. Drivers must detect this information as quickly as possible in order to return to their traffic lane. In the context of laboratory, this situation can be associated to a reaction time experiment. In the next section, the reaction time procedure and its application for the present study as well as details on the setup are presented.

3.1 Reaction time

A reaction time is defined as the delay between the apparition of a stimulus and the action of the participant in reaction to it. Donders [12] has defined three different tasks: a simple reaction time, a discrimination time and the reaction time to different choices. For a task measuring a simple reaction time, generally participants have to press a button rapidly when they hear (detect) a sound. The reaction time (RT) corresponds in this case to the minimum delay to detect a stimulus added to the necessary time of motor execution.

Concerning the reaction time to auditory warning, studies have shown that different parameters of an alarm can affect reaction time. Suied et al. [13] pointed out the influence of the rhythm on RT. Authors used auditory alarms built with pulses of 1000 Hz and duration of 20 ms, with different values of IOI (300, 100, 50, 33 and 20 ms) between the repeated pulses. The results indicated that the reaction time decreased with the IOI, with a threshold below 33 ms. In the current work, elaboration of the stimuli is based on this parameter.

3.2 Driving simulator

The test bench is a semi-realistic driving simulator developed by IFSTTAR. Participants were seated in a double-walled sound isolation booth (IAC) in front of computer screen depicting a road scene (Figure 3). Participants have to follow a road trajectory using a steering wheel; the experiment tasks are detailed in another section.

Figure 3: The test bench. The vibrating steering wheel is equipped with pressure sensors FSR. The computer screen depicts a road trajectory; a visual rectangle indicator (middle of the screen at the bottom) gives the pressure feedback on the steering wheel (green on the picture). Two pedals are used as response interface during experimental tasks.

The driving simulator is managed by a central software called DR2 [14] that runs the scenario (visual scenes and the starting time of the warnings). This software communicates with a microprocessor-based electronic board, which has been developed in a previous project, recording all the data (sampling rate: 1000 Hz) coming from the different sensors, like the FSR sensors on the steering wheel, the optical coder giving the angle of the steering wheel, and the pedal response. FSR sensors were used in order to control that the participants held the steering wheel with the same average pressure force range, all over the experiment. Minimum and maximum values of the range were defined in advance based on previous measures, and were indicated to the participants during the experiment by means of a rectangle visual indicator on the screen: the indicator was green whenever the force pressure was inside the range, and turned red when it went outside the range (respectively too weak or too strong). Participants were asked to control their pressure force on the steering wheel in order to keep the visual indicator green along the experiment.

When DR2 sends an alarm start during a scenario, the software Max/MSP sends the auditory warning and the vibratory warning through a RME Fireface 400 soundcard. The auditory warnings are played dichotically over closed headphones (Sennheiser HDA 200, Germany). A motor providing alternative angular variations of the steering wheel generates the vibratory warnings. The noise motor has been muffled. Nevertheless, we could not test the influence of the vibratory component alone, due to the experimental setup producing noise, even if the headphones attenuate passively the external sounds.

3.3 Reaction time experiment

In order to measure the perceptual influence of the vibratory component on the sound component of an ATLM, we used an objective measurement of urgency based on a simple reaction time measurement. Participants were asked to follow a trajectory (driving simulator) using the steering wheel (primary task), Figure 3. As soon as they perceived a stimulus they had to respond quickly by pressing the pedal (secondary task).

Two experimental conditions were used: unimodal condition (the sound component alone) and bimodal condition (the sound and the vibratory components together).

The vibratory component is transmitted by the vibrating steering wheel and the sound component by headphones.

Participants had to maintain their hand on the steering wheel with a specified pressure (see above).

The RT is measured by the difference between the time when the pedal is pressed and the time when the stimulus was played. This difference includes motor execution time, which is supposed to be similar for one participant over all the trails.

3.4 Stimuli

Stimuli are based on the analysis and re-synthesis of normalized physical measurements done by UTAC inside a vehicle, while driving (Laguna Renault car, France). A Bruel & Kjaer 4189 microphone was used to record the sounds inside the vehicle, Figure 4. A Bruel & Kjaer 4524 accelerometer was used to measure vibrations on the steering wheel, Figure 4. Measurements were done on the A11 French highway, with the vehicle crossing an ATLM (bumps of 1 cm high and 3 cm large with spacing of 0.7 meter) with a decreasing speed from 130 km/h to 90 km/h. Then, measures were analysed using a LMS Scadas mobile test lab.

The sound levels were around 77 dBA (130 km/h) and the vibrations corresponding to the acceleration of the fundamental frequency: 0.2g (x-axis), 0.1g (y-axis) and 0.1 (z-axis).

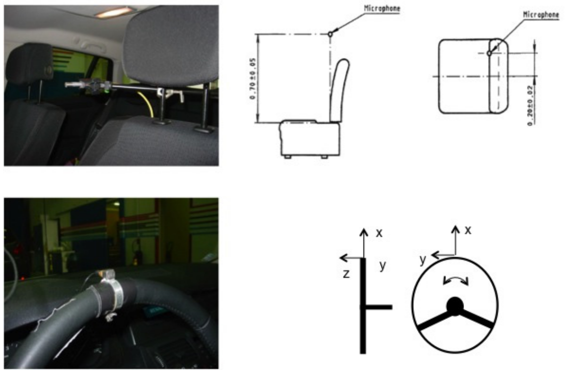

Figure 4: Position of the microphone Bruel & Kjaer 4189 (top) and the accelerometer Bruel & Kjaer 4524 (bottom).

Sound and vibratory components produced when crossing of the ATLM both have a harmonic content, Figure 5.

New auditory warnings sounds (and vibratory signal) were re-synthesised following the construction of an auditory alarm described in Figure 2, using MATLAB (R2008). First, a pattern of the sound signal (130 km/h) was selected corresponding to a period of the signal and used as a pulse. Second, this period was used to construct a burst. According to the literature, different values of the inter onset interval IOI (40 ms, 60 ms, and 90ms) were selected corresponding respectively to a periodic signal of 25 Hz, 17 Hz and 11 Hz. These fundamental frequencies were chosen to obtained perceptive differences in terms of rhythm rather than in terms of pitch [15].

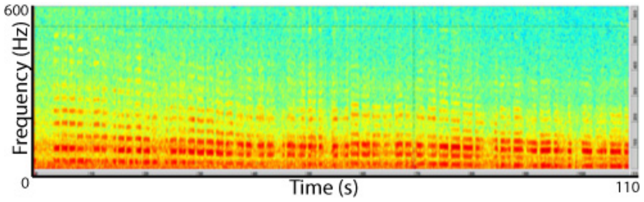

Figure 5: Time and frequency representation of an ATLM sound signal generate by a car with a decreasing speed from 130 to 90 km/h. The colours represent the level of the sound.

Each burst lasted 900ms (with an onset and offset respectively of 1 ms and 7 ms). A low pass filter was applied to each stimulus. The vibratory component of the warning is built with the same process.

In addition, values of the three fundamental frequencies were chosen in order to be perceptively discriminable (Just Noticeable Difference) for the sound component [16] and for the vibratory part [17]. Four levels of vibration were used: no vibration, low level, mid level and high level.

The sound corresponding to an IOI of 60 ms was calibrated at a level of 72 dB with a Mediator Bruel & Kaer 2238 sound-level meter, and the other sounds (IOI 40 ms and 90 ms) were perceptually adjusted to the loudness of the sound IOI 60 ms by 12 participants. The vibratory signal IOI 60 ms was calibrated with the same accelerometer as the measurements in a frequency band 5-70 Hz (low level: 0.45 g, mid level: 1 g and high level: 1.56 g). The levels of vibratory signals were equalized perceptually for each IOI (40 ms and 90 ms) using the 60 ms IOI alert as a reference. For each level (low, mid and high),15 participants could increase or decrease the vibratory level with pedals until they felt a good perceptual match between the signal they were setting and the reference signal.

3.5 The participants

Eleven volunteered participants (6 women and 5 men) were paid for their participation. The participants were between 20 and 39 years of age (median: 28.5 years) and they all had a driving licence. All reported having normal hearing, and no health problem linked to vibration exposure. All participants were native French speakers.

3.6 Experimental design

Reaction times (dependent variable) were measured changing the signal's physical parameters (IOI: 40, 60 and 90 ms) and the vibration levels (null, low, mid and high). The alarms were played randomly; the time between each alarm (duration of 900 ms) lasted between 3 and 8 seconds.

The experiment was divided in 4 sessions corresponding to the four levels of vibration. Each session was built with four blocks of 75 sounds (25 of each IOI). For each participant, we measured 100 reaction times for each couple of IOI and vibration level. The order of the sessions and blocks was randomized across the participants. Each session lasted around 45 minutes with break between blocks. Two sessions could not be performed within two consecutive days.

Participants were trained on a short block of ten alarms before starting the experiment.

To summarize, the controlled factors (dependant variables) were: the IOI (40, 60 and 90 ms), the vibration level (null, low, mid and high), the number of the block (1, 2, 3, 4), the repetitions (from 1 to 25), and the gender (man, woman).

4 Results

In the next section, raw data, ANOVA analysis and the conclusion will be presented.

4.1 Raw data analysis

We observed 11.87% of missing data. Missing data (MD) correspond to reaction times that we could not obtain because the participant missed the stimulus or because the participant did not press the pedal correctly. The second explanation is supported by the fact that a lot of missing data are associated with the woman's group (1174 missing data) contrary to the man's group (394 missing data). The pedal itself (a midi pedal) was not necessary well designed for different anatomies even if the experimenter controlled for each participant the good use of this device.

4.2 ANOVA analysis

The missing data were substituted by imputation using the mean of the reaction times for each participant across the 25 repetitions of each IOI, for each given block and for each given vibration level. As a consequence of the missing data distribution, two participants were excluded from the ANOVA. Indeed, missing data were predominant for specifics levels of vibration (78.7% of MD for the mid level of vibration for one participant and 88% of MD for the high level of vibration of the other participant).

The analysis was done with the data of nine participants (5 women and 4 men).

A 3 (IOI) × 4 (Vibration levels) × 4 (The number of blocks) analysis of variance ANOVA was performed. The within-group factors were the IOI, the levels of vibration and blocks with repeated data (participants). A Geisser-Greenhouse correction is used to take the internal correlation between repeated data into account.

No significant effect of the vibration levels on RT was observed, [F(3,24)df=3, F=0.436, NS], Figure 6, but the IOI appears to have a significant effect on RT [F(2,16) =8.005, $p < .05$], Figure 7. The data shows that the mean RT decreases when the IOI decreases (for IOI=40ms, M=366.9ms, SD=80.4; for IOI=60ms, M=369.9, SD=85.41; for IOI=90ms, M=377.54ms, SD=91.93ms). The shortest reaction time is associated to the IOI of 40 ms. A contrast analysis shows a significant difference between the mean RT for sounds with IOI of 40 ms and 90 ms and between RT for sounds with IOI of 60 ms and 90 ms but no significant difference between RT for sounds with IOI of 40 ms and 60 ms. These results are coherent with other studies [13] [18] [19]. No other factors and interactions have a significant effect on the RT.

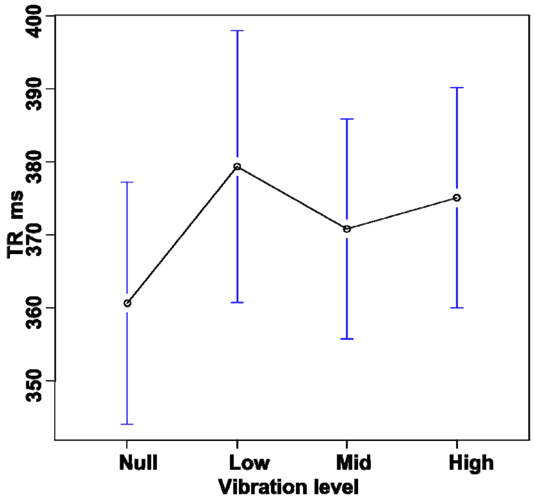

Figure 6: Interaction plot between the vibration levels (Null, Low, Mid, High) and the reaction time (ms) with the 95% confidence errors bars.

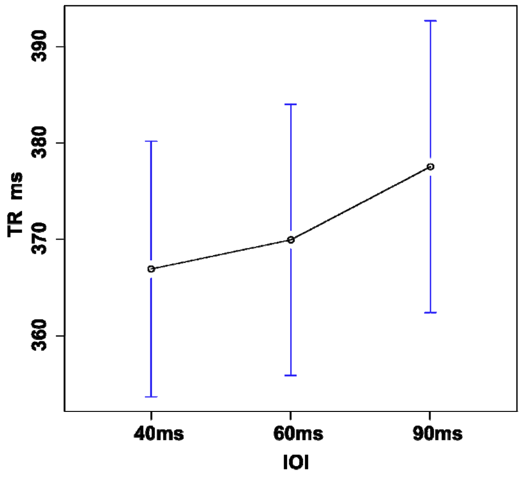

Figure 7: Interaction plot between the IOI (40ms, 60ms, 90ms) and the reaction time (ms) with the 95% confidence errors bars.

5 Conclusion

ATLM (audio-tactile lane-marking) on roads produce a bimodal signal, i.e. containing a sound and a vibration component, when a vehicle rolls over it, while unintentionally leaving the traffic lane.

The goal of our experiment was to study the perceptive influence of vibratory component on the sound component of an alarm by measuring reaction times. A simplified context of a driving situation was reproduced; participants had to press a pedal when perceiving an urgency situation.

The alarms were built with the model of Patterson [8] and physical measurements of ATLM (sound and vibrations). In agreement with experimental results of Suied et al. [13], the IOI between pulses extracted from measurements were diverse, as well as the vibratory component's levels of the alarm.

Results show no influence of the vibration on reaction times (steering wheel). This result is contrary to the study by Stanley [3] that used a vibrating seat but coherent with the result of Parizet et al. [2] in a different experiment.

This influence on reaction time is regardless of the level, but this is not true for the IOI: reaction times decrease when the IOI decreases. This result was obtained on a laboratory context even if a semi-realistic driving simulator was used.

The next steps of the RoadSense project will focus on how sound components can be shaped and modified in order to obtain quick reactions from a driver leaving the traffic lane.

Acknowledgments

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