The effect of Visual, Haptic, and Auditory Signals Perceived from Rumble Strips during Inclement Weather

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Abstract— Rumble strips (RS) offer ideal conditions for multimodality research. Designed to reduce crashes and alert drowsy or inattentive drivers, their effectiveness in crash reduction is not questioned but little is known regarding how information from tactile vibrations and auditory rumbling is integrated during low-vision driving conditions. In this paper, we report descriptive data related to participants’ perceptual experience while driving on a RS road during a snow storm, as well as data collected from participants driving in a simulated snow storm environment, and suggest future research perspectives.

I. INTRODUCTION

Rumble strips (RS) are an effective way of providing auditory and haptic feedback [1][2][3] to the driver. Since visual, auditory, and haptic (all senses related to touch, including proprioception and the kinesthetic sense) feedback play important roles in perceiving the road while driving a car, RS have the potential of alleviating problems arising from inclement weather conditions that reduce visibility and force drivers to rely more heavily on senses other than vision. While the effectiveness of RS in crash reduction is not questioned, little is known regarding how information from tactile vibrations and auditory rumbling is integrated during low-vision driving conditions. This proposed research will focus on the way drivers rely on different sensory modalities (vision, auditory, and haptics) to modulate and control their actions while driving on rumble strip roads under inclement weather conditions.

The potential of RS is subserved by the highly multisensory nature of our percepts in which sensory modalities are constantly integrated in order to modulate a driver’s actions (motor output) based on anticipated sensations, i.e., the expected sensory consequences of self-generated actions at specific points in time and space [4][5][6][7][8]. Indeed, behavioral changes resulting from sensory stimuli require the driver to constantly build rules between successive actions and sensations. This sensorimotor loop anticipates the effects of actions on sensations and contributes to understanding the stable world problem [9]. For instance, a driver acts in a specific way (e.g., turns the steering wheel in a specific direction) to verify an anticipated sensation (e.g., RS). Thus, establishing sensorimotor contingencies during driving will have major implications for understanding how humans integrate sensory information from the environment based on their cognitive expectations (i.e. how their intentions specify which perceptual events will occur as a result of an action).

Our future goal is to understand how sensorimotor information from RS is integrated during driving based on cognitive expectations. Indeed, drivers’ motor behavior is strongly related to inferred agency, especially when changing lanes or making left/right turns. Research has shown that drivers can still execute lane-change maneuvers when visual feedback is removed, as long as information from the vestibular and sensorimotor systems is available and the heading changes (due to changing into the adjacent lane) were explicit [16]. This suggests that drivers predict their steering wheel behavior based on previous sensory information as the consequence of an action [18][19]. When weather conditions are bad enough that it is not possible to rely on vision, the sensorimotor contingencies [20] change to adapt to the

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situation. Drivers have to relearn the contingencies between the actions they perform and the sensory signals they receive. All sensory information coming from the car or the pavement becomes crucial to driving accurately and safely toward their destination.

Here we report the results of two pilot studies. The first is an online survey that assessed drivers’ sensory experience while driving under low-visibility conditions (snow storms). The second is a driving simulator experiment in which we control the auditory and tactile feedback that drivers received from RS while driving under low-visibility conditions.

II. Survey Pilot Study

A. Participants

In an ongoing study, we asked drivers who drove at least once in the middle of a winter storm to describe their perceptual experience. Participants were NMU psychology students and were given course credit for their participation. Among 500 participants who participated in the survey, we retained only 342 participants who mentioned that they drove on a road where RS have been installed.

B. Procedure

Participants completed an online survey (taking approximately 15 minutes) via Qualtrics (Provo, UT) [21]. They were asked to describe their sensory experience while driving under low-visibility conditions. It consisted of 4 yes/no questions and 4 open questions, such as describing whether they relied on other senses (auditory, motor, etc…) to compensate the lack of vision and used the information coming from the rumble strips to direct their driving under low visibility conditions. It also contained demographics questions such as age and gender.

C. Results and Discussion

The preliminary data (Fig. 2) showed that drivers rely on the sensory information provided by rumble strips during bad weather. This result is not surprising since RS contribute to the enhancement of haptic and auditory feedback to compensate for the lack of vision. It also corroborates previous findings that showed vibrations or sounds produced by RS can be used to correct the driving trajectory [17]. When it is not possible to rely on the most dominant sense, in this case vision, drivers rely on other senses. Among the 342 participants, 59.46% stated that it was impossible to rely on their visual sense while they were driving in the middle of a snow storm (A, H, and A-H on Fig. 2). They described their visual experience in terms of a white or black (night drive) blank screen. Among them, 18.92% relied only on their auditory (A) sense, 19.73% used only their haptic (H) sense (tactile sensations from grasping the steering wheel; vibrations from the car and motor feedback from the brakes), and 20.81% used both their auditory and haptic (A+H) feedback to compensate for the lack of vision. 40.54% stated that they were still using the visual (V) sense in spite of low visibility (V, A+V, and V+H on Fig. 2). Interestingly, their description of their visual experience was different from the participants who did not rely on their visual sense. Although they were not able to see the travel lane, the weather conditions still allowed them to exploit other visual cues coming from the environment such as brake lights or tracks of previous cars, reflections from road signs or mailboxes, or street lights.

However, it is still not clear how some users decide to rely on either auditory sense, haptic sense, or both. One plausible explanation is that the sensory information coming from the senses is conflicting and does not match the cognitive expectations of the driver. A common statement was that the information coming from the rumble strips, although useful, did not provide them with relative direction (left vs. right). They knew that they were shifting from their lane because of the tactile vibrations and auditory rumbling, but it was difficult to know from which side. The drivers who relied on their auditory sense reported that they had to roll down their window or turn off the radio or the heat (in spite of negative temperatures). We believe that rolling down the window helped compensate for the lack of relative direction. Indeed, if the sound was louder on the drivers’ side, the RS would probably be on the centerline, whereas if the sound was softer, the RS would be on the shoulder.

In most cases, before feedback about the action to produce (shifting more to the left or to the right) becomes available, drivers rely on their previous sensorimotor experience of the sound produced by the RS (the first time they heard the sound before rolling down the window), which leads to expectations of specific sensory consequences (sound-RS association: louder-center; softer-shoulder).

Another interesting result is related to driver’s behavior toward the cold. It seemed that the drivers endured or ignored the cold (by turning off the heat and rolling down the window) because driving under extreme weather conditions was overwhelming and stressful and thus cognitive load was at the maximum. They needed most of their cognitive resources to keep focus on the information provided by their sensorimotor loop to understand which actions produce which sensations that in turn produce anticipated events.
III. DRIVING SIMULATOR PILOT STUDY

The driving simulator study aims at quantifying participants’ ability to use and integrate the auditory and tactile feedback from RS during inclement weather driving.

A. Participants

Eleven participants (M=28.6 years, SD=13.5) were recruited from McGill University and the greater Montreal area, and all received monetary compensation. The second and third author also completed the experiment. Driving experience ranged from 2 to 47 years (M=9.8 years, SD=13.0) and average kilometers driven each year ranged from 70 to 15,000 (M=4921.8 km, SD=6261.1). Eight participants were female.

B. Apparatus

The driving simulator (VS500M) was located at and developed by Virage Simulation, Inc. [22] located in Montréal, QC. The simulator included the driver’s seat and center console of a compact GM car, three 52” LCD displays (providing a front view of 180 degrees), a high fidelity 5.1 surround sound system, and a three-axis platform with electric actuators to simulate acceleration, engine vibration, and road texture feedback. The data were collected by the simulator at 8Hz and included the following variables: x, y, z coordinates of the vehicle, lane position, speed, steering angle, brake and gas pedal positions, and rumble strip warning status. The scenario developed by Virage Simulation, Inc. for the experiment involved a practice condition and four test conditions.

C. Design and Procedure

The experiment consisted of two practice trials that lasted approximately three minutes each, and four experiment trials, each of which lasted five minutes. Participants were recruited in groups of 2-4, and the trials for each participant were interleaved with those of the others to provide a break after each trial.

The first practice trial was to familiarize the participants to the simulator; they were instructed to drive down a freeway while keeping the car in the center of the lane, the speed consistent, and making minimal steering wheel movements. The second practice trial introduced the experimental conditions, in which the participant always drove in a straight line down a snow-covered road in conditions of low visibility. The participants controlled the speed and were instructed not to exceed 40 km/h (11.1 m/s). In the Auditory-Haptic (AH) condition, RS lined the shoulders of the road and provided haptic and auditory feedback to participants when the tires came into contact with them. The Auditory (A) condition provided participants only with the auditory feedback from the RS. The Haptic (H) condition provided participants only with vibrations when they made contact with the RS; auditory feedback was reduced through the use of both ear plugs and headphones. A final Baseline (BL) condition had no RS on the road and therefore no auditory or haptic feedback if participants drove onto the shoulder. For all four trials, visual cues (arrows) appeared on the screen if the participants drove too far off course, indicating the direction in which they must orient themselves to get back onto the road. Auditory feedback during the AH condition was provided by the mechanism that caused the rumble strip vibrations, while during the Auditory condition only a recording of the RS sound was played.

Participants were first seated in a conference room to read through the informed consent and instruction sheets. Then, the first participant was brought to the driving simulator and completed the first and second practice conditions, as well as the first experiment trial. The researcher then called upon the next participant, who followed the same procedure. When all participants had completed the first two practice conditions and their first experiment trial, the first participant returned to complete the second experiment trial, followed by the second participant, etc. The order of the four experiment trials were counterbalanced across participants. At the end of the experiment participants filled out a short questionnaire about their driving experiences.

D. Results

The effect of the different feedback conditions was assessed by calculating a variety of dependent measures: the standard deviation of the lateral position of the car; the amount of time the wheels where on either the left or the right RS; the velocity and the variability of the velocity of the car. We will address these different measures in turn.

Standard deviation of the lateral position. Compared to the baseline, the amount of lateral sway (Fig. 4a) tended to be less in the conditions with RS feedback. While a repeated-measures ANOVA did not show a significant effect of Condition (F(3,30)=2.49, p=0.11), contrast analysis reveals significant differences between the Baseline on the one hand, and the Auditory-Haptic condition (F(1,10)=13.3, p=0.004), and the Haptic condition (F(1,10)=9.38, p=0.012), on the other. There was no such significant difference between the Baseline and the Auditory condition (p=0.29).

Time spent across RS. We calculated the percentage of trial time in which the RS were engaged (i.e., duty cycle) (see Fig. 4b). A 2 RS (Left vs. Right) x 4 (Condition) repeated-measures ANOVA showed a significant main effect of Condition (F(3,30)=3.59, p = 0.025), and a significant interaction between RS and Condition (F(3,30)=3.46, p = 0.028). Because of the interaction we performed separate repeated-measures ANOVAs for left and the right RS. These
revealed no significant effect of Condition for the left RS (F<1), but a significant effect for the right RS (F(3,30)=6.13, p = 0.01). Contrast analysis showed significant differences between the Baseline on the one hand, and the Auditory-Haptic condition (F(1,10)=10.5, p=0.009), and the Haptic condition (F(1,10)=9.06, p = 0.013), on the other. There was a marginally significant difference between the Baseline and the Auditory condition (p=0.068).

Velocity and velocity variability. There was a tendency to drive below the allowed speed (Fig. 4c); although a repeated-measures ANOVA did not show a significant effect of Condition (F(3,30)=1.92, p=0.15), Bonferroni-corrected one-sample t-tests showed that driving speed significantly below the speed limit in the Auditory condition (t(10)=3.81, p=0.003). The variability in speed (see inset) was not significantly affected by condition (repeated-measures ANOVA: F < 1).

Questionnaire. Of the seven participants who replied that they had previous experience driving in extreme weather conditions, six reported that the rumble strips helped compensate for the reduced visual input, which corroborates the results of the survey where 88% reported that RS are useful. Similarly to the survey, five participants reported using rumble strips to adjust their vehicle to the left or right (out of the path of the rumble strip) while another participant reported driving as close to the rumble strip as possible to use it as a line to follow.

IV. CONCLUSION AND FUTURE PERSPECTIVES

The survey revealed that while 88% of the participants agreed that RS are essential and effective while driving under low-vision conditions, their description in terms of sensory experience was not quite clear. The results of the simulator study suggest that the Auditory-Haptic and the Haptic conditions have beneficial effects: a reduction in lateral sway, less time spent across the RS, and no slowing down. The Auditory condition, on the other hand, had none of these beneficial effects. In fact, it appears to have had some effect in that it produced a significant reduction in driving speed. Since there was no difference between the Auditory-Haptic condition and the Haptic condition, it is reasonable to assume that the beneficial effects are due to the haptic aspect of the sensory feedback; although it can be argued that the effect of the haptic aspect of the sensory feedback is potent enough to offset any effects introduced by the auditory aspect. The simulator study was limited in that there was only a relatively small sample which could have affected its statistical power in identifying potentially more nuanced effects of the various feedback conditions. In addition, the age range was relatively broad. Future work would benefit from studying the effects of aging on the ability to utilize and integrate the various sources of sensory feedback [23].

It would also be interesting to explore how individual differences and the level of expertise of the driver contribute to the potential of RS. Driving is a complex task and, depending on the drivers’ experience, it can be either automatic or controlled processing [24]. An experienced driver would coordinate pedals and steering automatically and unconsciously while beginners must pay attention to the way they operate the pedals while turning the steering wheel, all of which require conscious and controlled processing. During inclement weather or when traffic conditions become difficult, the process is rarely automatic even for an experienced driver. They use all their cognitive resources to concentrate on their driving. They will use more than one sense, if not all their senses to focus on the task.

Finally, these results will contribute to theoretical frameworks on multimodal integration and, at a broader level, to the “stable world problem”, the idea that in all sensing modalities, individuals have the ability to experience a continuous and stable world in spite of the fact that
stimulation changes constantly [9]. This research will also contribute to the evidence base for vehicle design and driver safety for all regions in which extreme snowy weather conditions are experienced.

REFERENCES


