EFFECTS OF HAPTIC VERSUS VISUAL MODALITIES WHEN COMBINED WITH SOUND IN FORWARD COLLISION WARNINGS

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Abstract - The Crash Warnings Interface Metrics study showed that seat belt pretensioning in Forward Collision Warning (FCW) situations reduced driver response times significantly. This study examined whether that effect is limited to haptic belts, or is a general effect of haptic warnings. 48 participants received FCWs in critical lead vehicle braking situations while doing a visual distraction task. Three FCW types were tested. A warning sound was combined with either seat belt jerks, a brake pulse or a visual warning in a head up display. All FCWs made drivers abort the distraction task and look up. Furthermore, combining sound with seat belt jerks or a brake pulse lead to significantly faster response times than combining the sound with a visual warning. These results indicate that faster response times may be typical for haptic warnings in general. They also suggest that future FCWs should include a haptic modality to improve driver performance.

Keywords: forward collision warning, haptic warnings, driver distraction, brake response time, simulator event design

1 Introduction

For a Forward Collision Warning (FCW) system to be effective, the warning it issues has to (re)direct the driver’s attention to the forward roadway and make him/her respond appropriately in typical pre-crash situations. Numerous studies have been carried out to understand the extent to which different FCWs succeed in doing so [Abe1, Abe2, Abe3, Che1, Jam1, Kra1, Sco1, Ler1].

One outcome of these previous studies is that presenting the FCW in more than one modality, for example by combing an auditory and a visual warning, elicits quicker responses than single modality warnings.

The question that follows is of course which modalities to combine. In a recent paper [Sch1], Euro NCAP indicated that it will require FCWs to be loud and clear, which suggests a combined auditory/visual warning. However, other combinations may elicit even quicker response times.

In the Crash Warnings Interface Metrics (CWIM) report [Ler1], all FCWs that included seat belt pretensioning gave faster driver responses than those that did not. However, as that study did not include other haptic alternatives, it was not possible to conclude whether this was a general effect of adding a haptic modality, or a specific effect of using seat belt pretensioning to warn.

The present study aimed to address this particular question, i.e. whether adding a haptic modality is generally beneficial or if the effects are limited to seat belt pretensioning only.

The study tested three different FCW types. All had the same auditory warning but differed in their additional modality. The first added seat belt pretensioning to the sound, the second a brake pulse and the third a visual warning in a head-up display (HUD).

One more topic, regarding response validity, was also addressed in the study. Among others, the recent 100 Car Naturalistic Driving study [Din1] has shown that real world situations where FCW would be useful, i.e. where emergency braking is required to avoid collision with a lead vehicle, typically occur very unexpectedly from the driver's point of view.

To properly replicate these real life scenarios in an experimental setting, and thus get a valid assessment of whether a particular FCW would help or not, each simulated critical event should therefore ideally come as a complete surprise to the test person. This is very difficult to achieve, and a key challenge for simulator study design [Lju1]. In the present study, the magnitude of potential expectancy effects was studied by including a second repetition of the critical scenario.

2 Method

A critical lead vehicle braking event including a visual driver distraction task was implemented in a moving-base simulator.

2.1 Participants

48 subjects, 15 women and 33 men participated in the study. All subjects had normal or corrected-to-normal vision, and had held a driver's licence for more than 5 years with a total driving experience of at least 50 000 km. All participants also had previous experience of the driving simulator, because they were recruited from a larger pool of previous participants. However, none of the subjects had previous experience of FCW, and they were not informed about there being FCW in the vehicle. Each subject was given 30 € for their participation.

2.2 The driving simulator

A high-end moving base driving simulator, located at VTI, Linköping, Sweden, was used. The vehicle mock-up was a Saab 9-3 Sport sedan MY 2003 with automatic transmission. The visual system consists of 3 DLP projectors (1280x1024 pixels) providing a 120 degrees forward field of view. Edge blending and geometrical correction is provided by a dedicated graphics card. There are 3 LCD displays incorporated into the rear view mirrors for rearward views. Sound from vehicles, road and wind is simulated and presented via the in-vehicle speaker system. The moving base has three parts: a linear sled, a tilt motion system and a vibration table. The sled can provide linear motion with an amplitude of ± 3.75 m at speeds up to ± 4.0 m/s and accelerations up to ± 0.8 g. The tilt motion system can produce pitch angles between - 9 degrees and + 14 degrees and roll angles of ± 24 degrees. The vibration table gives ± 6.0 cm in vertical and longitudinal movement, with a maximum roll angle of ±6 degrees and pitch angle of ± 3 degrees.

2.3 Event design

The lead vehicle braking event took place on a simulated 4-lane divided motorway with 2 lanes in each direction, in daylight conditions and with no precipitation (dry surface), with a moderate density of ambient traffic travelling in the opposite direction to the subject vehicle (henceforth referred to as SV), and some slower moving traffic travelling in the same direction as the SV. Subjects were instructed to maintain the posted speed limit of 90 kph. The lead vehicle in the two conflict scenarios (henceforth referred to as the Principal Other Vehicle, POV) was always of the same model and colour in order to keep brake light contrast constant.

The primary task was to drive on a motorway for approximately 30 minutes. The participants were instructed to drive as they normally would under similar circumstances and keep the speed limit (90 km/h). There was oncoming traffic at an average rate of three vehicles per minute and other cars overtook the participants once a minute on average. They also caught up with slower vehicles which they had to overtake on average once every two minutes.

A key goal for the study was to assess braking performance in kinematic conditions sufficiently critical to elicit true emergency braking reactions. As discussed at greater length in [Eng1], this is challenging since drivers tend to adapt their behaviour in anticipation of critical events.

For this study, a scenario previously shown to be effective in tricking subjects into violating their safety margins [Lju2] was used with slight modifications. The SV initially travels in the right lane at speed v_1 (self-paced). The POV overtakes in the left lane at speed v_2, and then at a time headway of 0.9 seconds moves back into the right lane. The POV then continues to move away from the SV at speed v_2 until it reaches a time headway of 1.5 seconds. Here, POV speed is first instantaneously set to SV speed minus 5 m/s, and then the POV brakes at a rate of 0.55 g. To keep the time from when the POV starts to change lanes until it is in braking position constant across variations in SV speed, the POV speed was continuously adjusted to a predetermined fraction (1.15) of SV speed.

2.4 Visual distraction tasks

To make the drivers look away from the forward roadway from time to time, they were from time to time instructed to carry out certain in-vehicle tasks, including phone dialling, radio tuning and changing the sound settings. A special visual distraction task from Ford's VIRtual Test Track EXperiment (VIRTTEX) [Lju2] was also used. In this task, drivers are prompted to read back a sequence of 5 numbers (randomized single digits between 1 and 9) appearing on a display positioned far down to the right (approximately 45 degrees down angle). Each number is shown for 0.3 seconds with 0.2 seconds of blank screen in between, creating a total task duration of 2.3 s. It was during this special task that the critical event was triggered. To motivate drivers to complete the numbers task, they were told that their responses would be randomly checked for correctness. Each task was initiated by a pre-recorded voice message instructing the driver task what to do and the details of the tasks.

Drivers were prompted to initiate a task on average once every 2 minutes of the drive. In the lead vehicle braking events, task initiation was automatically triggered based on POV position to ensure that the distraction task overlapped with the POV braking event.

2.5 The Forward Collision Warnings

The FCW was given in three ways, by combining a warning sound with either seat belt pretensioning, a brake pulse or a visual display. The belt pretensioning consisted of 5 belt jerks of 150 ms duration with 150 ms pause between each jerk. The visual warning was given by flashing a series of LED-lights mounted on the dashboard, projected upwards. When lit, the LEDs are not directly visible to the driver, but their light is reflected in the windscreen, conceptually mimicking the effect of flashing lead vehicle brake lights. Each visual warning consisted of six of 125 ms duration with 125 ms intervals in between. The auditory warning consisted of a sound very similar to the one developed in the CAMP project for FCW [Kie1], which is used in all Volvo Cars with FCW up to MY2013. The sound was presented at 74.5 dB A. The Brake Pulse took the form of a triangular deceleration pulse of 400 ms duration with a peak value of 2,2 m/s^2.

The study used the FCW warning algorithm described in [Jan1], which is similar to the improved CAMP algorithm [Kie2]. Due to the event dynamics described above, the triggering threshold was reached almost immediately upon POV brake onset. The FCW was thus issued on average 300 ms after POV brake onset.

2.6 Experiment design

FCW type was included as a between-subject variable while event exposure was a within subject variable. All subjects were exposed to two critical lead vehicle braking events that were intermingled with non-braking events, where a similar POV did overtake without braking, and non-critical braking events, where a similar POV overtook and then turned on the brake lights without decelerating, but the FCW was made to trigger anyway. There was a total of 24 events along the route. First came 15 non-braking events, then the first critical event. Then came two non-critical braking events intermingled with 5 non-braking events. Last, the second critical event occurred. The first three minutes of the drive did not include any events. The entire drive took 27 to 30 minutes to complete.

2.7 Dependent variables

A number of dependent variables were defined to characterise the process of responding to the braking POV. *Gaze Response Time* represents the time from POV brake onset to the first driver glance on the forward roadway, i.e. when the driver looks up from the visual distraction task screen. For eye-tracking, a four-camera system running Smart Eye Pro 5.9 was used.

Accelerator release time represents the time from POV braking onset until the driver has released the accelerator pedal fully. In this study, negative accelerator release times were allowed, to capture any expectancy effects especially in the second critical scenario.

Response time represents the time from POV braking onset to initiation of a driver response. Response times were determined by first calculating *Brake* and *Steer onset times*. The driver’s response time was defined as the shortest of these two times.

2.8 Procedure

To minimise any initial expectations of critical events, the subject was told that the purpose of the study was to collect general data on normal driver behaviour for later use in other projects. The subject was instructed to drive as s/he normally would, with no extreme manoeuvres, and to maintain the posted speed of 90 kph.

Before commencing the practice drive, the subject practiced all in-vehicle tasks until s/he felt comfortable doing them. Then followed a ten minute practice drive. The practice drive did not include any braking or steering events of critical character, only normal steering and two instances of normal braking to a full stop. Towards the end of the test drive the subject again practiced the secondary tasks, until s/he felt comfortable performing the task while driving.

After the drive, the experimenter revealed the true purpose of the study. Subjects were debriefed and an interview was conducted.

3 Results

Data was subjected to a 3*2 mixed ANOVA with Condition (FCW type) as between-subjects factors and Exposure (First and second critical event) as a within-subjects factor. Data was analyzed with the SPSS general linear model using type III sums of squares.

3.1 Response times

The average Gaze Response Time (GRT) was about 570 ms, and this was similar across all FCW types and events, i.e. there were no main effects of either FCW type or Exposure.

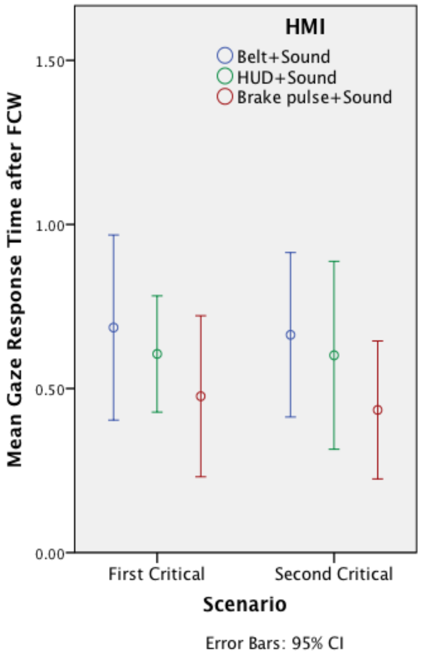

Figure 1: Average gaze response times per FCW type and scenario

There was a main effect of FCW type for Accelerator Release Time (ART) ($F(2, 44)=5.2$, $p=.01$). Pairwise comparison of the FCW types within each scenario showed that drivers with Belt/Sound warning and Brake Pulse/Sound warning released the accelerator approximately 300 ms faster than drivers with HUD/Sound in the first scenario, though these differences were not statistically significant ($p=.232$ and $p=.146$ respectively). In the second scenario, drivers with Belt/Sound were 350 ms faster than drivers with HUD/Sound ($p=.024$) and drivers with Brake Pulse/Sound ~280 ms faster than drivers with HUD/Sound (not significant).

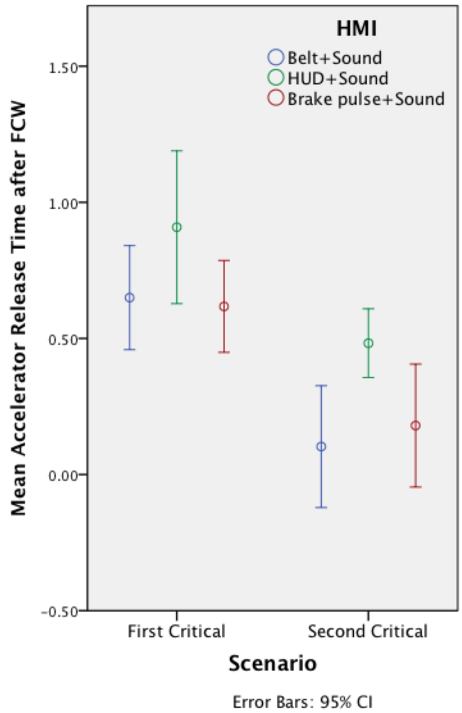

Figure 2: Average accelerator release times per FCW type and scenario

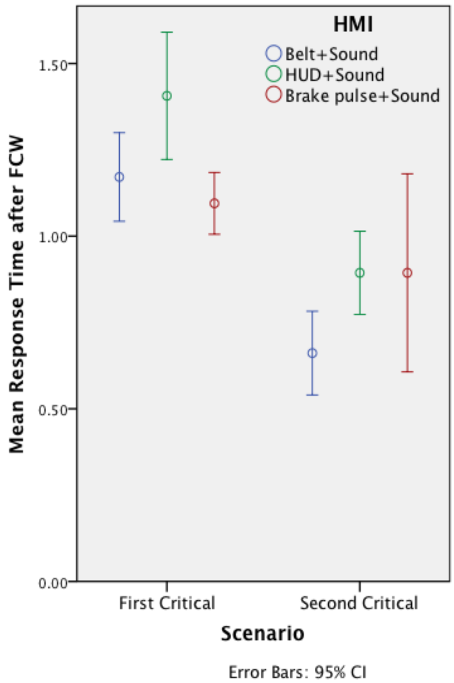

Figure 3: Average response times per FCW type and scenario

There was a main effect of FCW type for Response Time (F(2, 43)=6.8, p<.004). Response times were significantly reduced with ~440 ms in the second scenario (F(1, 44)=44.9, p<.001). Also, ART variability did increase with repeated exposure, due to occurrences of anticipatory responses (negative ART values).

Pairwise comparison of the FCW types within each scenario shows that drivers responded to both Belt/Sound and Brake Pulse/Sound approximately 300 ms faster than to HUD/Sound in the first scenario (p=.016 and p=.024 respectively). In the second scenario, drivers with Belt/Sound were 200 ms faster than drivers with HUD/Sound (p=.024) and drivers with Brake Pulse/Sound ~100 ms faster than drivers with HUD/Sound (not significant). Response times were also significantly reduced with ~440 ms in the second scenario (F(1, 43)=137.9, p<.001).

In terms of avoidance type, braking was the predominant maneuver. Only one driver did steer to avoid collision. Over the full event series, there was one collision.

4 Discussion

The results for GRT shows that all FCW types were effective in redirecting the driver's attention back to the forward roadway, i.e. all FCWs made the drivers look up from the visual distraction task. Regarding differences between the FCWs, the groups who received a haptic warning in combination with the sound both showed significantly faster response times than the group who got the auditory/visual warning.

This indicates that the faster driver responses with seat belt pretensioning found in [Ler1] may be typical for haptic warnings in general and may not restricted to seat belt pretensioning only. The response time difference found in this study is roughly of the same magnitude as found in [Ler1], so this study can be said to corroborate those findings.

This indicates an interesting route for future research, which is to go deeper into the possible underlying mechanisms whereby a haptic input leads to a faster "situation check" on behalf of the driver. It also suggests that future FCWs could benefit from including a haptic modality to improve driver performance even further.

The second topic for the study was to investigate whether a truly surprising event could be created. In the first scenario, when drivers looked back to the road after the warning, the situation was perceived as critical enough to elicit an emergency response, and the response time magnitudes are in line with those for really unexpected events [Gre1]. The scenario design thus was successful in creating a truly surprising event.

In the second scenario however, both RT and ART were significantly shorter, with magnitudes in line with those for drivers who know something will happen, but not what it is [Gre1]. The presence of negative ART values also suggest that some drivers began to adopt more proactive response strategy, e.g. releasing the accelerator already when the POV changed lane. The second event can therefore not be classified as truly surprising.

Two caveats regarding the study should be mentioned. First, drivers were not encouraged to practice braking in the test drive, to avoid inducing motion sickness. No artefacts were expected from this, as feedback from previous studies in this simulator indicate that braking is perceived as normal and realistic right from the start. However, the lack of braking practice may have influenced the results in some way.

Second, the drivers were completely naive to FCW, i.e. did neither know that the vehicle was equipped with a warning system nor had any previous experience with similar systems. This may not be fully realistic, since real-world drivers with FCW in their vehicles would have developed a stronger association between warning and response over time, and hence may respond faster or differently in this type of scenario.

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