No other significant findings related to LDU or Modality were present. As a result H_{3b} was accepted and H_{3c} was rejected.

Results for LatDev and SteAng both show a differential effect of Situation and Time in the driving metrics. While in situations Car and Stim the metrics improved after a situation arose, this was not the case for CarStim.

DISCUSSION

Response Times

The results for response times indicate a clear advantage of using warnings in synergy with a critical event in the driving task (H_{1a} was accepted). This result addresses the research space highlighted by [2,27], providing clear evidence that there is an effect of situational urgency in driver warnings. While there were no differences in terms of RT for the simple Car and Stim conditions, when these events occurred together in CarStim, there was a pronounced effect in how quickly people reacted. This also extends the results of Ho & Spence and Ho, Tan & Spence, where spatially predictive audio [12] and vibrotactile cues [14], meaning cues that correctly predicted the direction of an approaching threat, resulted in better reaction times compared to their non-predictive variants. A similar result was also found when combining multimodal audio and visual cues [22]. In the present study, it became clear that the advantages of providing combinations of audio, visual and tactile cues hold not only when they predict the direction but also the existence of a critical event.

In terms of the modalities used, there was an advantage of multimodal warnings over unimodal ones in terms of RT, since A, T and V warnings were all slower than AT, AV, TV and ATV ones (H_{1c} was accepted). This advantage of using more than one modality to alert drivers has been discussed in several previous studies [11,20,26]. However, never before has this effect been shown in all modality combinations and with a braking task, rather than just a button pressing task as in [27]. In the driving context, there seems to be an additive effect of conveying the same information across more than one sensory channel. Possible explanations of this effect will be attempted in future work, investigating the fit of human data to known models of multisensory perception, such as the Race Model [29]. As will be discussed later, this advantage in RT does not necessarily come with a similar advantage in other metrics, such as LatDev and SteAng. Even so, the benefit of using multimodal signals in the driving task, especially when signifying critical situations, is clear.

The level of designed urgency of warnings was another factor that influenced responses (H_{1b} was accepted). Warnings of high designed urgency elicited significantly quicker responses, even with no prior information related to the type or content of the message given to participants. When asked after each experimental session which properties of the signals in their opinion affected the perceived urgency of a stimulus, participants identified interpulse interval, colour and frequency in almost all cases. This result extends prior work like [2,20,27] by evaluating reaction time across unimodal, bimodal and trimodal combinations of warnings and in varying contexts of situational urgency. Guidelines related to fundamental frequency of sounds, colour for visuals and interpulse interval for all three modalities used [9,19,24] seem to apply uniformly in the driving task. These should be considered when designing driver displays, as the resulting warnings elicit quicker responses when designed to be highly urgent. This is an important conclusion especially as the cues used in this study provided no information on the event they signified. Future work will explore the influence of using richer multimodal cues than those used here and evaluate whether these benefits will hold also in that case. Previous studies such as [12,20] have looked at the efficacy of informative driver displays, but there is need to evaluate how such cues combine multimodally and what type of information is best delivered in which modality.

Finally, there was a significant decrease in performance when encountering warnings involving the visual modality in situation CarStim. None of the advantages of ATV warnings over AT ones, TV ones over AT ones and V warnings over A ones were present in situation CarStim. This indicates that the benefits of visual signals as driver displays can be limited when there is high visual load in the task at hand. The presentation of a car braking was visual and in combination with visual signals it seemed to damage rather than benefit the response times. A similar disadvantage of the visual modality was found in [25]. In [22], there was also an advantage of audio over visual displays when a visual indicator to a critical situation was provided. This result extends [27], where multimodal signals involving visuals created quicker responses, but in absence of any visually demanding events in the driving task. Horrey & Wickens [17] also found that response times to a critical event degraded when voice dialling was aided by a head-down display. Although we used no side task in our study, these results also suggest a cluttering of the visual modality during a visual critical event. As a guideline, visual warnings should be avoided in road events of high situational urgency, and signals involving audio or tactile modalities should be preferred, as they reduce the visual load of driving.

Lateral Deviation and Steering Angle

The results of LatDev and SteAng showed a differential effect of Situation on the driving metrics. Situations Stim and Car both led to improved lane keeping behaviour and to less variation in the steering angle (H_{2a} and H_{3a} were accepted). However, this effect was not present in situation CarStim. In terms of SteAng, values were significantly higher after situation CarStim arose. However, the disturbance to the driving behaviour reflected in SteAng was not high enough to also increase values of LatDev (see Figures 4.a and 4.b). In any case, for both LatDev and SteAng there was no improvement in situation CarStim.

This result can be accounted to the increased workload created by situation CarStim. The simultaneous onset of warnings and a critical event may have created a startle effect, similar to the one observed in [4], where participants' control over the simulated vehicle was poor when critical warnings were delivered. This also comes in line with some participants' comments, mentioning that situation CarStim was startling. Along with the observed increase of reaction times to signals including the visual modality, this observation provides evidence for how the increased amount of visual information can affect driving performance. Lindgren *et al.* [21] and Liu [23] also observed poorer lane keeping and steering behaviours when using visual as opposed to audio displays to aid non-critical tasks (list selection [21] and navigation [23]). Although no differences in terms of modalities were found in our study, the findings of Lindgren *et al.* and Liu also add to the argument that visual load is increased during driving. The addition of a critical visual event as CarStim in the present study could only have added to this load.

From the results of LatDev and SteAng several conclusions can be derived. When there is no critical situation demanding attention, multimodal warnings seem to improve drivers' alertness and lead to a better driving behaviour. The benefit of this effect disappears when there is a visual task demanding immediate action, such as situation CarStim. Although response times improve when a multimodal signal is presented in situation CarStim, lane keeping behaviour is neither improved nor worsened by the cues. Quicker reactions are essential in more critical situations, so the benefits of multimodal cues are valuable in this context. However, lane keeping performance is also essential when there is no imminent critical event, so the benefit of multimodal cues in this case is still present.

Finally, there was a marginally better performance in terms of SteAng for warnings at L_M and in situation CarStim (H_{3b} was accepted). It appears that warnings of L_M aided driving behaviour in terms of SteAng more than the ones of L_L or L_H. Combined with the result of intermediate response times achieved by these warnings, they seem a good option to facilitate overall alertness for drivers in situations that require quick but not immediate responses. Interestingly, these situations, for example low fuel, were the ones that these warnings were designed to address.

CONCLUSIONS

This study investigated the effects of varying situational urgency on the response times, lateral deviation and steering angle of participants in a simulated driving task. Three situations were simulated: a car braking without warnings, warnings without a car braking and both simultaneously. The results showed a clear reduction in response times to warnings when the critical event in the driving scene occurred at the same time as a warning. Quicker responses were observed when responding to bimodal and trimodal warnings compared to unimodal ones and to warnings of high urgency compared to medium and low urgency. Further, the use of visual warnings slowed responses in the critical situation, providing evidence of high load in the visual modality. This effect was also observed in lateral deviation and steering angle values, where the benefit in driving metrics when there were either warnings or a critical event, was not present when the event arose together with the warnings.

These results extend knowledge of in car warning design by identifying the effect of situational urgency on participant response times as well as driving metrics. They also verify the benefit of using multimodal displays of varying designed urgency to alert drivers in a context of varying situational urgency, a case not previously simulated. The evidence of high visual load during a critical event highlights the limitation of the visual modality when encountering critical events in the driving scene. A unique feature of this study is that it investigates the effect of multimodal displays on driving metrics in detail, evaluating driver responses to each combination of modality and situation. Assessing these metrics in such detail showed the differential effect of providing warnings to the lane keeping and steering behaviors. These results indicate the utility of multimodal driver displays when requiring immediate responses and the potential of non-visual warnings to decrease driving workload.

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