



Visual in-car warnings: How fast do drivers respond?

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ABSTRACT

We investigate how quickly drivers can change lanes in response to a visual in-car warning. Our work is motivated by technological developments, in which beacons along the road can trigger in-car warnings, for example when a driver is approaching a lane closure. What is not known, however, is at what distance such an in-car warning still allows for a timely lane change. We measured how quickly drivers respond to a visual in-car warning in a driving simulator. The driving task was combined with an audio task that provided different levels of cognitive distraction. We found that the initial reaction time to in-car warnings was significantly larger for drivers that were distracted by the audio task. Although the majority of drivers responded in time for a safe lane change, some drivers occasionally missed these signals, pointing at a serious potential hazard. Indeed, the results of a simulation model, used to investigate how this might extrapolate to regular traffic conditions, suggest that around 50% of drivers might not make a timely lane change in response to a last-minute warning. This indicates that these signals might be insufficient on their own when applied in the real world. This work can inform the design and evaluation of safer roads and in-car interfaces.

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1. Introduction

Roadwork sites have a higher crash rate than the same roads without roadworks (Khattak, Khattak, & Council, 2002). For example, a meta-review of accidents in the Netherlands (van Gent, 2007) suggests that a failure to miss roadwork signs can result in various accidents such as rear-end collisions and crashing into roadwork safety trailers. Given the safety risks of such accidents, it is important to consider ways to prevent them.

One option to potentially reduce these accidents is the use of in-car technology to timely signal a critical event, such as an upcoming lane closure, to the driver. A specific technology that has been identified for this effort is to place beacons that can transmit wireless messages to cars equipped with an appropriate receiver (cf. IEEE, 2010). This technology can be used to display visual warnings in a car and as such allows for warning a driver for an upcoming traffic event. These beacons could be used on roadwork safety trailers (Fig. 1) to inform drivers of an upcoming lane closure.

What is unknown, however, is whether an additional warning within the reach of the trailer beacon would allow the driver sufficient time to make a timely, and safe lane change. Current estimates of the reach of such beacons is approximately 500 m (Gozálvez, Sepulcre, & Bauza, 2012; Paier, Faetani, & Mecklenbrauker, 2010). Moreover, in some countries like the

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Fig. 1. Roadwork safety trailer. Used with permission from Rijkswaterstaat. Source: <https://beeldbank.rws.nl>, Rijkswaterstaat.

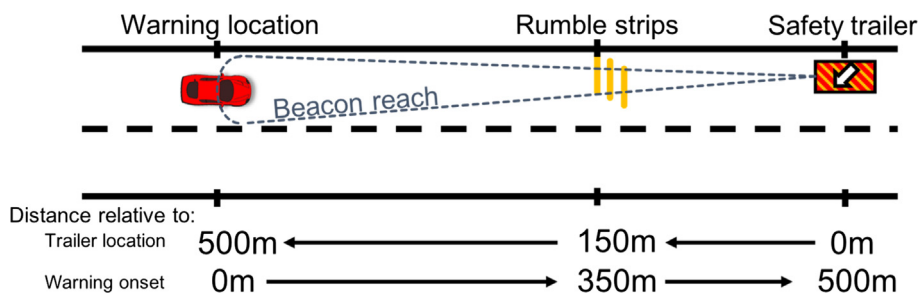


Fig. 2. A typical roadwork scenario as you can encounter it in the Netherlands: a beacon, placed on a roadworks trailer, warns for an upcoming lane change. Distances can be expressed relative to the trailer and relative to the location where the car first received the warning, as determined by the beacon's reach (i.e., 500 m). Please note that in Dutch roadwork scenarios, a trailer is typically preceded by rumble strips. Our experiment provides a controlled version of this scenario, in which a warning is given, but no trailer or rumble strips are visible to the participant.

Netherlands these roadwork trailers are also preceded by portable rumble strips (also known as sleeper lines), which serve as a tactile warning and are the last resort to warn people to change lanes. Usage of rumble strips is prescribed by guidelines (e.g., for the Netherlands these are: CROW, 2013). In the Netherlands rumble strips are placed 150 m before the trailer, which already takes up 150 m of the beacon's reach. In effect, usage of rumble strips reduces the distance to make a lane change after receiving the in-car signal to 350 m (500–150 m), as also shown in Fig. 2. However, is this enough distance to make a fast and safe lane change? We investigate this in the current study, by studying how fast drivers are able to respond to a sudden in-car warning that informs them about upcoming roadwork.

More specifically, we investigated lane change performance while placing drivers under different levels of cognitive distraction using an audio task (cf. Kunar, Carter, Cohen, & Horowitz, 2008). Previous naturalistic driving studies have shown that drivers are distracted by various tasks such as eating, smoking, conversations, and making phone calls (Dingus et al., 2016; Klauer et al., 2014), similar to how distraction plays a role in many other professional and private situations (e.g., Janssen, Gould, Li, Brumby, & Cox, 2015). Even tasks that do not require you to take your hands off the wheel, such as holding a conversation (e.g., Iqbal, Ju, & Horvitz, 2010; Janssen, Iqbal, & Ju, 2014) or responding to cued words (e.g., Kunar et al., 2008; Strayer & Johnston, 2001), can distract from driving and result in longer response times. In effect, such distractions lead to a higher accident risk (Dingus et al., 2016; Klauer et al., 2014). It is therefore important that the performance of changing lanes within a distance of 350 m is investigated under different levels of cognitive distraction.

1.1. Preceding studies on lane changing

Lane changing is, next to lane keeping, a common practice on motorways. A lane change is defined as a driver maneuver that moves a vehicle from one lane to another where both lanes have the same direction of travel (Fitch, Lee, Klauer, Hankey, & Sudweeks, 2009). Lane change has been the topic of several studies (e.g., Finnegan & Green, 1990; Hetrick, 1997; Wakasugi, 2005) in which, for example, timings, crash rate, and the use of indicators has been studied.

The Human Factors Guideline for Safer Road Infrastructure states that a lane change can be split up in two stages: an orientation and an approach stage. Each stage takes around 2–3 s before actual movement is initiated (Birth, Pflaumbaum, Potzel, & Sieber, 2009). However, in practice multiple action stages can be identified such as checking the mirrors, shoulder check, indicating direction of the lane change, and making a steering movement. Under some circumstances, a lane change could also involve braking or accelerating (e.g., to avoid crashing into a car that unexpectedly gets in a driver's lane).

In our simulator study, we look at the most basic version of a lane change, which consists of just the steering action. Our motivation for this choice is that measuring this action provides an estimate of the *minimum* time that is needed to change lanes. If even this minimum time is not sufficient to change within 350–500 m (our context of interest), then this suggests that actual implementation of systems that require a lane change within 350–500 m might need to be reconsidered.

1.2. Intended contribution and overview

The intended contribution of this work is twofold. First, we gain more theoretical insight on lane change behavior. Second, a practical contribution is to identify whether this lane change time is sufficient in our context of interest: beacons that provide a lane change alert 500 m before a roadworks site and 350 m before rumble strips appear. This investigation is particularly needed, as 350 m is a lot shorter than current guidelines that are used in Dutch road design (Dubbeldam & Vervoer, 2007; Kroon, Brookhuis, Hagenzieker, & Martens, 2014) allow (namely: around 675 m). Stated differently, our work can inform the evaluation of these guidelines in the face of new technology.

In this study we use a visual signal to deliver an alert. Although other types of alerts are possible in everyday systems (e.g., auditory alerts), we chose for a visual alert, for practical reasons. Our distracting task (discussed next) was presented auditory, and we did not want direct competition for cognitive resources (cf. Wickens, 2002; 2008). By separating visual signals (lane change warning) from auditory signals (secondary task), we minimize such interference.

In the remainder of this document, we will outline our driving simulator study in which we test how much time drivers need to react (i.e., a plain steering action without mirror checking or other gaze behavior) to an in-car signal and change lanes. After we present our empirical results, we use empirical data from Robinson and colleagues (Robinson, Erickson, Thurston, & Clark, 1972) to predict how these results would extend to real traffic situations where there is (need for) gaze behavior. Robinson and colleagues made detailed measurements of eye-gaze under different traffic conditions, which we apply to see how much longer lane changes are expected to last when made under traffic conditions. Hence, this simple model allows us to interpret how our empirical results might scale to an on the road situation where a lane change involves more steps, for example due to the presence of other traffic and the need for mirror- and shoulder checks.

2. Method

We tested how quickly drivers react to a visual in-car warning in a driving simulator set-up. Participants had to change lanes after receiving a visual in-car warning of an upcoming lane closure. We combined this lane change task with an audio task that created different levels of central cognitive interference: no audio task, simply repeating a word, or generating a word based on the last letter of the audio stimulus word (Iqbal et al., 2010; Kunar et al., 2008; Strayer & Johnston, 2001). Since in-car and external distraction is diverse (Dingus et al., 2016; Klauer et al., 2014), we chose this audio task as it is known to create central interference (Kunar et al., 2008; Strayer & Johnston, 2001). Central interference is independent of the modality of the task interaction (e.g., is not specific to visual, manual, or auditory interaction). By studying central interference, our setting therefore generalizes to various task interaction and modality settings. Such generalization is needed, given the diverse types of tasks that drivers perform in their cars (Dingus et al., 2016; Klauer et al., 2014).

2.1. Participants

Twenty-four participants (9 women; 15 men) ranging in age from 28 to 70 years ($M = 46.5$ years, $SD = 12.4$ years) were recruited by a recruiting company using quota sampling. The sample matches the distributions of highway drivers in the Netherlands on age, gender and yearly driving distance as found in a population-based study (CBS, 2013). Each participant had a driver's license for at least 3 years, drove at least 5000 km per year ($M = 14,000$ km), and had normal or corrected-to-normal vision. Only Dutch native speakers were recruited as the test involved verbal reaction to the audio task in Dutch. Participants self-reported to have no visual or auditory difficulties. All participants gave written informed consent, and were compensated with 35 euro.

2.2. Material & stimuli

Participants sat on an adjustable fixed chair in front of a Logitech G27 racing wheel and a 29" monitor (see Fig. 3A). In both single and dual-task condition the lane change performance was studied in the context of a visual warning. In the dual-task trials, participants were asked to steer a simulated car while performing an audio task at the same time. We will explain these individual tasks next.

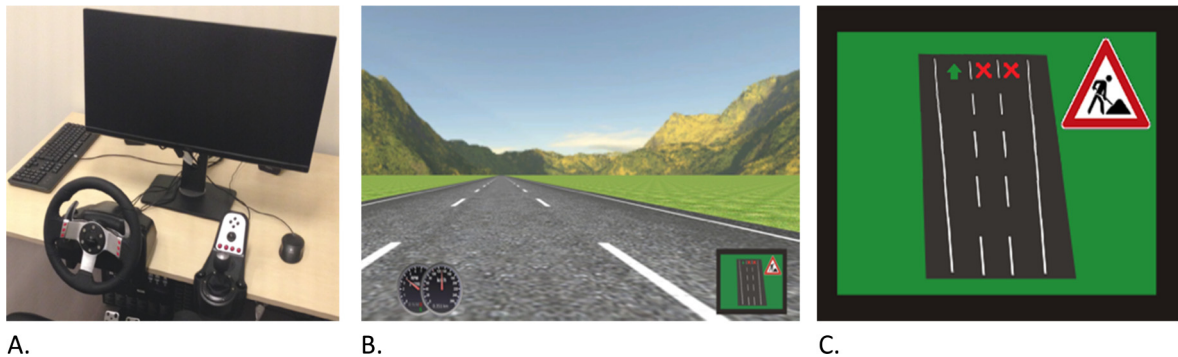


Fig. 3. (A) Driving simulator hardware setup, (B) simulated highway, with the simulated navigation display situated in the bottom right, (C) close-up of the simulated navigation device with closed lanes warning.

2.2.1. Driving task

The driving task was developed in a modified version of OpenDS 2.5.¹ OpenDS (Math, Mahr, Moniri, & Müller, 2013) has been applied in over 40 psychological studies worldwide (see <http://opensds.de/community/studies-using-opensds>). The driving task was to stay in the middle lane (3.5 m wide) of a straight three-lane highway. A simulated navigation system was shown at the bottom right of the screen (see Fig. 3B). This representation approximates the size of a Dutch navigation system. The symbols (visual cues) were about 1 degree in visual angle. When a lane closure was imminent, the interface showed which lanes were closed (red crosses), following symbols that are used on Dutch highways to indicate closed lanes. Participants were instructed to change to the open lane once they noticed the alert. The open lane was either to the left or the right of the central lane. The visual cue for lane closure was only shown on the interface, not on the road.

The car drove at a constant speed of either 80 km/h or 130 km/h (on Dutch highways the maximum speed is always between these values). Within a block of trials, participants changed lanes 6 times (half left, half right). For each lane change a trajectory of 1000 m was used. The upcoming lane closure was signaled at one of six locations (225, 275, 325, 375, 425 or 475 m after trial start), which were balanced over trials and subjects. At the end of each trial the car was automatically reset to the middle lane to begin a new trial, and the navigation screen was cleared (showing only a green background).

2.2.2. Audio task

We compared lane change performance in reaction to a visual warning in single-task driving to two situations where an audio task created distraction. The audio task is similar to the verb-generation task that is commonly used in psychology (e.g., Abdullaev & Posner, 1998; Snyder, Abdullaev, Posner, & Raichle, 1995) and is a task that is known to result in central interference in cognitive processing (Kunar et al., 2008; Strayer & Johnston, 2001). In both our audio conditions (i.e., *repeat* and *generate*), participants heard a stream of words, presented at a steady pace of 1 word every 4 s. In the repeat condition, participants simply had to repeat the word they heard. In the generate condition, participants had to respond with a new word that started with the last letter of the word they heard. For example, if they heard “plot”, they could respond with “top”. Previous work has suggested that the generate condition creates more central cognitive interference compared to the repeat condition in dual-task situations (cf. Kunar et al., 2008; Strayer & Johnston, 2001).

To generate the word set, we selected 4 letter Dutch words from an online database (www.woordenraden.nl). For each letter of the alphabet, we identified a set of words that started with that letter. We then sorted words by their last letter and manually removed words that were uncommon in Dutch language, or emotionally loaded, as judged by the experimenter. If more than 20 words remained for a particular last letter, at most 20 words were selected. For some letters (e.g., words ending in ‘x’) fewer, or no words remained. The final set consisted of 315 words.

The words were converted to audio via a text to speech processor and were played over headphones. The participants’ vocal response was recorded with the headphone’s microphone. Recording was done in two separate streams: one stimulus stream and one response stream. In addition, the experiment leader used a paper form to keep track of which words had an incorrect response or other error. This detailed multi-faceted recording allowed for accurate offline evaluation of time intervals between word presentation and first response.

2.2.3. Subjective experience

After each condition, subjective experience was assessed using raw TLX (Hart & Staveland, 1988).

¹ We changed the physics of the default OpenDS implementation of a car, such that our car would accelerate instantly instead of gradually.

2.3. Design

We used a 2 (Driving speed: 80 km/h, 130 km/h) \times 3 (Audio task: No audio, Repeat, Generate) within-subjects design. Conditions were blocked by speed level. Half the participants started with 80 km/h, the other with 130 km/h. Within each speed condition, participants completed all audio conditions in a blocked fashion. All participants started with the *no audio condition*. This was followed by the *repeat* and *generate condition*, of which the order was counterbalanced. The order of audio conditions that was used for the first speed level, was also used for the second speed level.

2.4. Procedure

Upon arrival, the procedure was explained and an informed consent form was read and signed. Next, all tasks were practiced to ensure that participants were familiar with them. First, the repeat and generate audio task were practiced with ten samples each. Second, participants practiced two single-task driving trials for the 130 km/h speed level and followed by one dual task trial.

Participants then performed six experimental blocks. After each block, participants filled out the TLX questionnaire. Finally, participants completed 20 single-task audio trials (10 repeat and 10 generate trials), to assess single-task audio performance. The total procedure took approximately 70 min. Participants were allowed to take short breaks in between blocks.

2.5. Measurements

We were interested in how lane change times change as a function of driving speed (80 km/h vs 130 km/h) and the amount of distraction (no audio, repeat, generate). To this end, we analyzed four facets of behavior:

1. *Initial reaction time* was defined as the time it took before the first steering movement exceeding 1 degree was made (T1 in Fig. 4) relative to the onset of the in-car warning (T0). The initial reaction time is a proxy of how long it takes drivers to initiate a lane change after first stimulus onset. For each condition, we calculated drivers' mean initial reaction time. As the simulator logged steering reaction time since presentation of the visual stimulus, some of these steering movements are not in response to the visual presentation (but due to ongoing steering movements). To compensate for this, we removed reaction times that were logged as being faster than 500 ms. If a looser criterium is set (e.g., 50 ms), the effects remain the same. Depending on the criterium, some effects might become slightly less pronounced.
2. *Lane change distance* was defined as the distance that was traveled between when the in-car warning showed (T0) and the moment at which the car was fully in the target lane (T2). The criterion for considering the car to be fully in the target lane was that the full body of the car passed the center of the lane markings. Note that the simulator only logged the timestamp of the lane change (i.e., T2), not the distance. The distance was calculated based on the known constant speed and the measured lane change time.
3. *Audio reaction time* was measured as the time it took to respond after an audio cue was played, as a proxy of cognitive distraction. We used the two audio streams for this analysis: a stream that recorded the audio stimuli and a stream that recorded the participants' vocal responses. Both streams were stored in one file and thereby synced in time. Audacity (audacity.sourceforge.net) was used to automate the search of audio responses. A threshold of 20 dB was used to discriminate silence (including slight noise) from audio responses. The automated procedure only detected audio responses that were at least 1.5 s apart within the same audio stream. After the automatic detection, each response stream was checked and corrected manually for artifacts such as "Uhhh", loud breathing, and coughs. In cases where there was no audio

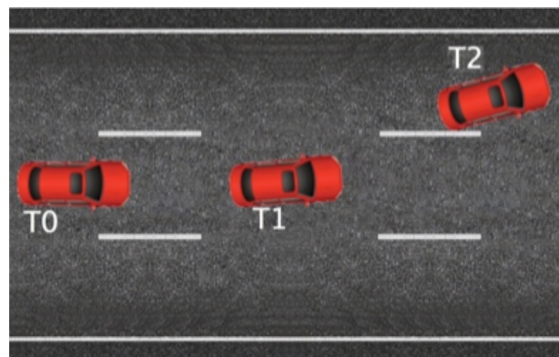


Fig. 4. Measurements overview showing the critical timestamps in the experiment. At T0 the visual warning is first presented. At T1, the participant makes the first (bigger) steering action. At T2 the car is fully in the target lane.

response to a stimulus, this stimulus-response pair was removed from the analysis. For three participants, this analysis was hindered by continuous loud breathing (i.e., which connected multiple sound fragments). These participants were removed from the audio analysis.

4. *Subjective workload* was measured using the TLX questionnaire, where participants scored their workload on a scale from 1 to 20 on various subscales (Hart & Staveland, 1988). We analyzed the score on the mental demand subscale.

Unless otherwise indicated, all metrics were analyzed using a 2 (Driving speed: 80, 130 km/h) \times 3 (audio condition: none, repeat, generate) analysis of variance (ANOVA) with an alpha of .05 for significance. Holm-Bonferroni-corrected post hoc tests were applied in the case of pairwise comparisons.

For some trials, the simulator output indicated that participants failed to change lanes within the maximum measurement time (10 s). For the analysis of initial reaction time (T1-T0), these trials were removed. However, for the metric of lane change distance, we replayed video clips of individual trials to verify the cause of the miss. In cases where participants simply did not change lanes (7 trials) or had not fully changed lanes before the measurement ended (11 trials), total lane change times (T2-T0 in Fig. 4) were set to the total measurement time: 10 s. This can be considered a minimum estimate of how slow drivers respond to an in-car warning, as the longest reaction time is hard-coded to 10 s (i.e., if the trial finished later, then reaction time might have taken even longer).

3. Results

3.1. Initial reaction time (T1-T0)

Fig. 5A presents the initial reaction time in all conditions (i.e. time interval T1-T0 in Fig. 4). There is a significant effect of the generation task on reaction time, $F(2,46) = 8.398$, $p < .001$, $\eta_p^2 = .27$. A post hoc test confirmed that reaction times were longer in the *generate* condition ($M = 1.52$ s, $SD = 0.52$ s), compared to the *repeat* ($M = 1.25$ s, $SD = 0.30$ s, $p = .006$) and the *no-audio* condition ($M = 1.24$ s, $SD = 0.30$ s, $p = .006$). There was no significant difference between the *no-audio* and *repeat* condition ($p > .1$). The initial reaction time at 80 km/h ($M = 1.33$ s, $SD = 0.45$ s) was not significantly different from that at

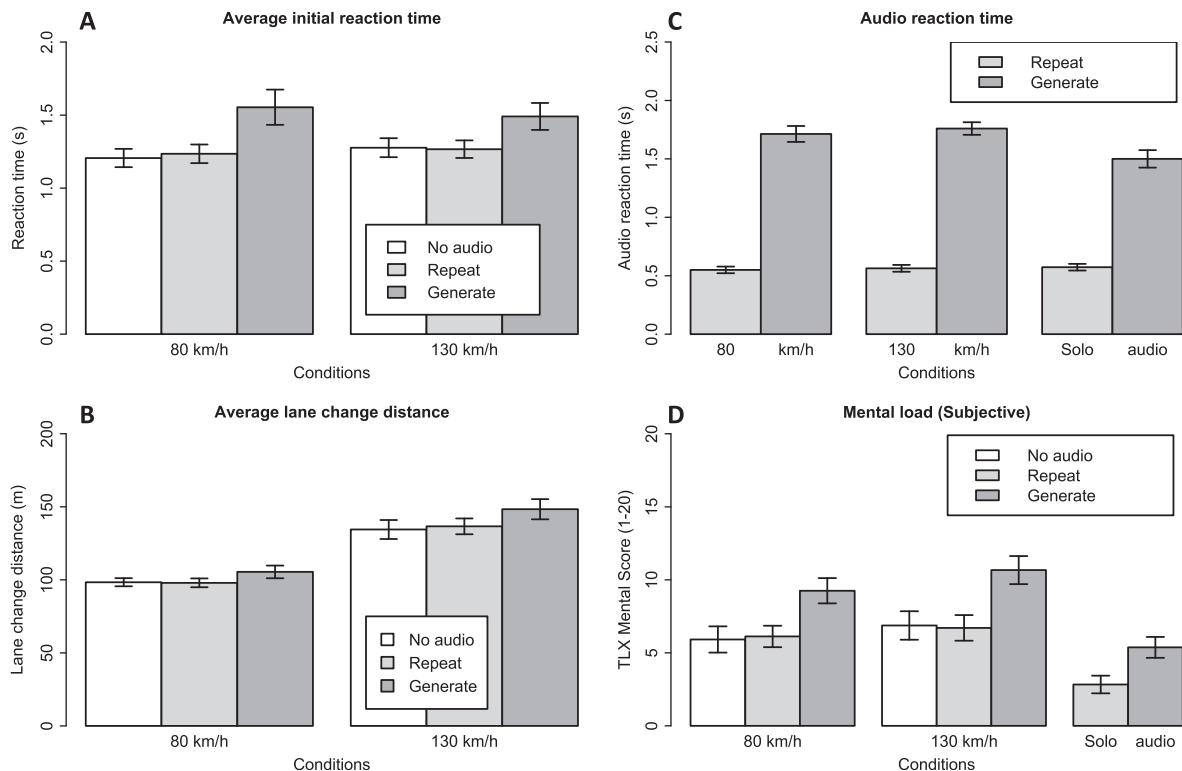


Fig. 5. (A) Bar graph of the average initial reaction time (T1). The graph shows that participants react significantly slower in the generate condition compared to no audio and repeat. (B) Bar graph of total average lane change distance (at T2) in different conditions. (C) Bar graph of the average audio reaction time to the different audio conditions. Responses took longer in the generate condition compared to the repeat condition. (D) Bar graph of the average indicated perceived mental load by participants. The generate condition was perceived significantly higher on mental load compared to the repeat and the no audio condition. All error bars indicate standardized error of the mean.

130 km/h ($M = 1.35$ s, $SD = 0.37$ s), $F(1,23) = .042$, $p > .1$. There was no significant interaction between speed and audio condition, $F(2,46) = 0.803$, $p > .1$.

3.2. Lane change distance (distance covered during T0 until T2)

Fig. 5B shows average lane change distance. Overall, the lane change distance was significantly shorter at 80 km/h ($M = 101$ m, $SD = 17$ m) than at 130 km/h ($M = 140$ m, $SD = 31$ m), $F(1,23) = 80.96$, $p < .001$, $\eta_p^2 = .78$. There was also a significant effect of audio condition, $F(2,46) = 3.434$, $p = .041$, $\eta_p^2 = .13$. Although the mean lane change distance was largest in the *generate* condition, a post hoc test did not find any significant difference between the *generate* ($M = 127$ m, $SD = 35$ m), *repeat*, ($M = 117$ m, $SD = 29$ m) and *no audio* condition ($M = 116$ m, $SD = 30$ m) (all $p > .1$). There was no significant interaction between speed and audio condition, $F(2,46) = 0.686$, $p > .1$.

3.3. Audio reaction time

Fig. 5C shows the average reaction time on the audio task. The audio data was analyzed using a 2 (audio condition: *repeat* or *generate*) \times 2 (driving speed: 80, 130 km/h) ANOVA. The average audio reaction time was significantly higher for the *generate* condition ($M = 1.7$ s, $SD = 0.3$ s) compared to the *repeat* condition ($M = 0.6$ s, $SD = 0.1$ s), $F(1,20) = 440.9$, $p < .001$, $\eta_p^2 = .96$. There was no significant difference between the two driving speeds $F(1,20) = 1.04$, $p > .1$. There was also no significant interaction between audio condition and driving speed, $F(1,20) = 0.33$, $p > .1$.

We performed an additional 2 (audio condition: *repeat* or *generate*) \times 2 (number of tasks: *single-* or *dual-task*) ANOVA to test whether dual-task audio reaction time differed from single-task audio reaction time. Again, audio reaction time was significantly higher for the *generate* condition ($M = 1.7$ s, $SD = 0.3$ s) compared to the *repeat* condition ($M = 0.6$ s, $SD = 0.1$ s), $F(1,20) = 333.4$, $p < .001$, $\eta_p^2 = .94$. We also found a significant effect of the number of tasks, $F(1,20) = 11.96$, $p = .002$, $\eta_p^2 = .37$. However, there was also a significant interaction between audio condition and number of tasks, $F(1,20) = 21.22$, $p < .001$, $\eta_p^2 = .51$. Post-hoc tests show that for the *generate* condition, performance is significantly slower in the *dual-task* compared to the *single-task* condition ($p < .001$). However, for the *repeat* condition there was no significant difference between *single-* and *dual-task* ($p > .1$). Taken together, these differences are consistent with the literature that generating new words is more demanding than repeating a word and therefore causes more dual-task interference (Kunar et al., 2008; Strayer & Johnston, 2001).

3.4. Perceived mental load (subjective)

Fig. 5D shows the perceived mental load indicated on the raw TLX questionnaire. There was a significant difference between the three audio conditions on perceived mental load, $F(2,46) = 37.71$, $p < .001$, $\eta_p^2 = .62$. A post hoc test showed that perceived load was significantly higher in the *generate* ($M = 10.0$, $SD = 4.3$) compared to the *repeat* condition ($M = 6.4$, $SD = 3.8$; $p < .001$), load was also significantly higher in the *generate* condition compared to the *no-audio* condition ($M = 6.4$, $SD = 4.2$; $p < .001$). However, there was no significant difference between *repeat* and *no-audio* ($p > .1$). There was also a significant effect of driving speed on perceived mental load, $F(1,23) = 5.189$, $p = .003$, $\eta_p^2 = .18$. Mental load while driving at 130 km/h is significantly higher ($M = 8.08$, $SD = 4.32$) compared load at 80 km/h ($M = 7.10$, $SD = 3.70$). There was no significant interaction between speed and audio condition, $F(2,46) = 0.722$, $p > .1$.

As can be seen in Fig. 5D, in general the perceived mental load was lowest when the participant was not driving at all (*solo audio condition* – the two right-most bars).

4. Discussion of results

Taken together, the results present a coherent pattern. When drivers are distracted by a secondary task, the impact on lane changing depends on the nature of the secondary task. In particular, the *generate* task created more subjective workload (Fig. 5D), increased reaction times on the audio task (Fig. 5C), and in effect also delayed the initiation of a lane change (Fig. 5A). This pattern is consistent with previous work that demonstrated in other dual-task settings that a word *generate* task is more distracting than a *repeat* task and a *no-audio* task (Kunar et al., 2008; Strayer & Johnston, 2001).

The distance that was traversed to complete a lane change (Fig. 5B) was influenced by the speed of the car, but not by the type of distracting secondary task. An effect of secondary task might be lacking on this metric, because the effect that the secondary tasks have on initial reaction time is relatively small (around 300 ms) compared to the time it takes to complete a lane change (e.g., 3900 ms for 130 km/h, 4500 ms for 80 km/h). Therefore, by the time the lane change is completed the initial difference might have been compensated for. The average lane change distance was well within the required distance of our context of interest (i.e., within 350 m). However, the traffic circumstances in the simulator were relatively ideal (i.e., no other traffic). In addition, as we will see next, there were some important individual variations.

In our experimental study we had to control for other sources of variation such as mirror and shoulder checks, to allow more accurate measurement of the impact that auditory distraction might have on a lane change. Although this allowed for

better detection of effects, we are aware that actual lane changes involve more steps. We will address these issues next using a simulation model where we integrate data from previous studies into our findings, this way we are able to get an idea of the effects of these additions to a more complete lane change task. The simulation model uses previous empirical data to account for these other known sources of variability, to make a projection of the expected distribution of lane change distances in less controlled (non-lab) environments.

5. Analysis and model prediction of distribution of distances

5.1. Analysis of distribution of human data

Our preceding analyses have focused on average reaction times and average lane change distances. For everyday life, however, it is not the average that matters, but the distribution of data – as the whole spectrum of drivers from slowest to fastest needs to be anticipated in the design of roads and technology. In particular, even if on average most drivers make a lane change on time, this is not a safe situation if one or more drivers does not make it and ends up in a crash.

To understand the distribution of lane change distance data, Fig. 6 shows a histogram of individual trial data, with one figure for all trials (i.e., showing all audio conditions) from the 80 km/h condition (top) and one for the 130 km/h condition (bottom). In this figure, the horizontal axis shows what distance is traveled before a lane change was completed, with 0 being the starting point at which the signal was given on the in-car device. In the scenario that we introduced in the introduction, a roadwork safety trailer would be standing at 500 m, and this would be preceded by rumble strips at 350 m (i.e., 150 m before the roadwork safety trailer) (CROW, 2013). Both distances are highlighted with a vertical bar. Our measurement lasted for a total of 10 s after the warning was shown. The bump at the end of each distribution represents the measurements where people had not fully changed to the target lane at that point and where we took the full 10 s as value. These measurements (18 trials in total) would normally be part of the tails of the distributions, which is now absent due to the hard 10 s cutoff.

As the figure shows, even in our relatively simple set-up with ‘ideal circumstances’ (e.g., no other traffic), in some trials drivers did not react in a timely manner to prevent driving over the rumble strips. Taken together, these data suggest that implementing a last resort signal at 500 m before roadworks start might not be timely for at least some drivers.

5.2. Model prediction of distance in real-traffic

The above scenario is relatively simple. For example, there is no other traffic and therefore no need to look in the mirrors and to signal a lane change before changing. In real traffic, these steps would be necessary. We therefore investigated what the impact of these steps is using a simulation model that takes these steps into account. The use of simulation models to predict human behavior in traffic situations is valuable (e.g., Brumby, Janssen, Kujala, & Salvucci, 2018; Horrey, Wickens, & Consalus, 2006; Janssen & Brumby, 2010; Janssen, Brumby, & Garnett, 2012; Salvucci, 2001; Salvucci, Mandalia, Kuge, & Yamamura, 2007). One advantage of such models is that they can give new insights about situations that are challenging to observe in everyday life, for example because they concern rare events. Moreover, models can give an indication of how likely such scenarios or rare events are to occur.

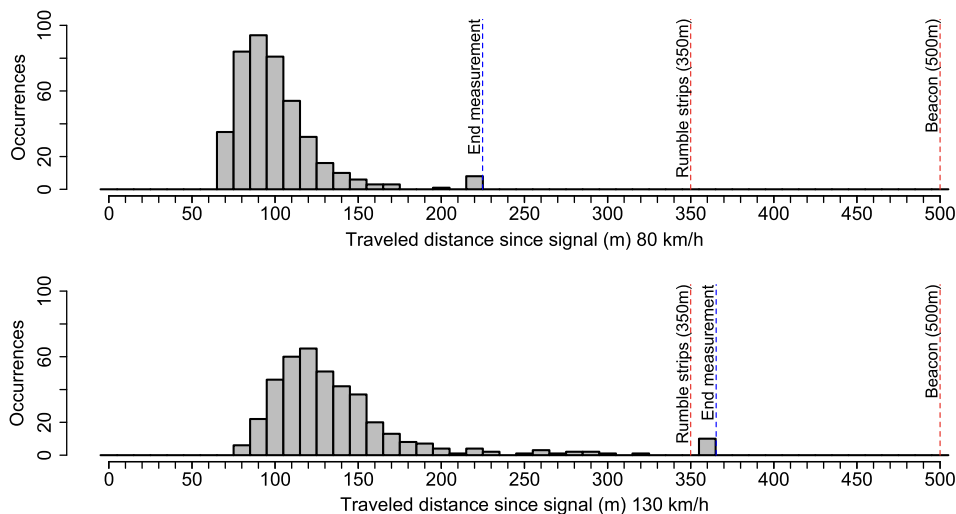


Fig. 6. Distribution of lane change distances since onset of the in-car signal (0 m). For comparison, we indicated the point at which a beacon is placed (500 m), the start of rumble strips (350 m) and the point at which our measurement stopped (361 m for 130 km/h, 222 m for 80 km/h; this is 10 s after the onset of the lane change signal). The top Figure shows distances when driving at 80 km/h, the bottom Figure shows distances for 130 km/h.

The starting point of our model is the article by Robinson et al. (1972), who measured lane-change times on the highway for eight drivers that drove at a slow speed (48 km/h). The researchers explicitly assessed the time that each aspect of visual search, related to the lane change, took: looking in the mirrors, making a head-movement to check for other traffic, and remaining visual search time (see Table 3 in Robinson et al., 1972). For our analysis, we took the data for a scenario with other traffic when merging to the left ($M = 6.10$ s, $SD = 0.56$ s) or to the right ($M = 4.53$ s, $SD = 0.30$ s).

We then ran Monte Carlo simulations to estimate the resulting lane change times when our human data of 80 km/h and 130 km/h would be combined with the estimated glance times from Robinson and colleagues. For each speed condition and each turn direction (left or right), we ran 100,000 simulations. For each simulation, we took a random data point from our experimental data of that speed condition, and combined this with a sample that was drawn from the distribution of the corresponding turn direction as measured by Robinson and colleagues (e.g., a normal distribution with $M = 6.10$ s, $SD = 0.56$ s for left turns). This resulted in four datasets with 100,000 duration estimates each. Using the driving speed, these lane change times were then transformed in lane change distances (expressed in meters).

Fig. 7 shows the resulting distributions. The top figure shows data for the 80 km/h condition, the bottom row for the 130 km/h condition. The left plots show data for changing lanes to the left, the right plots show data for changing to the right. Each Figure again plots a line for the location of the roadworks (500 m; red solid line) and of the rumble strips (350 m; orange dashed line).

When comparing Fig. 7 to Fig. 6, it becomes apparent that the added glance times have shifted all distributions further to the right. At 80 km/h (top), between 1% (right lane change) and 2% (left) of the simulated data points crossed the 350 m border (rumble strips), and none crossed the 500 m border.

For the 130 km/h condition, results are more dramatic. The 350 m border is crossed by between 42% (right lane change) and 53% (left) of the simulated data points. The simulation predicts that the roadwork safety trailer (500 m) would even have been hit by between 3% (right lane change) and 5% (left lane change) of the instances.

Using these simulations, we can also get a better estimate of the minimum distance at which one would need to place the rumble strips such that no driver (in this case: no simulation) might hit them. This is the furthest distance after which the model might have changed in time. In our simulation, this was 618 m. Assuming that a roadwork safety trailer is placed 150 m further down the road (compared to where the rumble strips starts), an in-car signal would need to be received at least 770 m before the position of the roadwork safety trailer.

As these data are based on simulations, the exact values are less informative than the general trend in the data. The trend is very consistent: in situations where drivers rely on the last-minute warning, sending this warning 500 m before the roadwork safety trailer will not be early enough for over 50% of the drivers. In order to make a safe situation, the distance

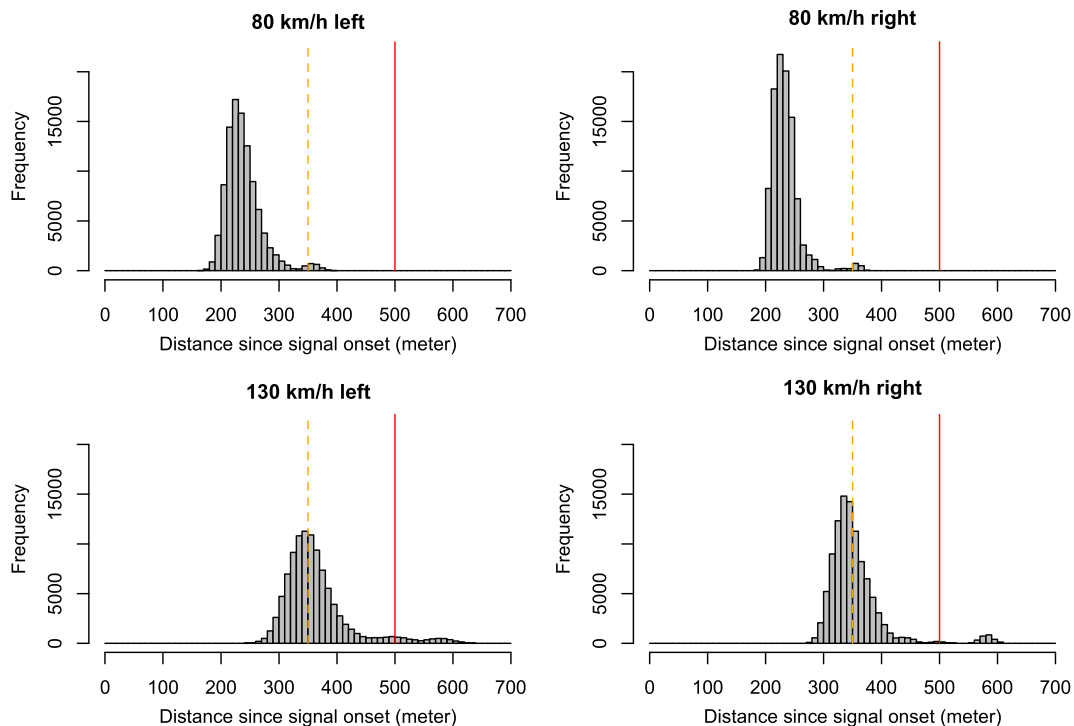


Fig. 7. Histogram of model predictions of lane change distances when making a turn to the left (left plots) or right (right plots) at 80 km/h (top plots) and at 130 km/h (bottom plots). A red solid bar indicates the location of the roadworks (500 m after signal onset) and dashed orange line indicates the location of the rumble strips (350 m).

between the signal and the roadwork safety trailer needs to be increased with over 50% of the current technological estimated capacity (Gozálvez et al., 2012; Paier et al., 2010): from 500 m to 770 m.

Even this estimate might still be a minimum for three reasons. First, whether one can change lanes will also depend on how much traffic is present. Changing lanes on a busy road can take more time. This is included implicitly in our model, as the model sampled from a distribution of data that included other traffic (Robinson et al., 1972). This same article showed that changing lanes took at least 1 s longer when other traffic is present (the data we used) compared to when no traffic was present. However, as traffic volume increases, this time might increase further. Second, in our dataset some participants did not change lanes within the given time frame. We assigned a lane change time of 10 s to these cases, but in reality, this might be more. In Fig. 7 these data points lead to the slightly higher bump at the far end of the tail of the distribution. In reality, this tail would be distributed over points to the right of it. Third, and finally, in our experiment participants knew that they would have to change lanes in every trial. This is not always the case in real driving.

6. General discussion

We investigated how fast drivers respond to visual in-car warnings. Our experimental results demonstrate that although participants in general were able to change lanes in time (i.e., within 350 m after receiving an in-car warning), there were also participants that missed these warnings (see Fig. 6). In practice, such participants would have hit the rumble strips. In our experimental results, the misses happened both in conditions where drivers were performing a secondary audio task, and in the condition where they were not.

A model simulation suggests that under real traffic conditions, the estimated number might be even higher: over 50% of drivers might not have enough time to make a lane change before they hit rumble strips, and around 3–5% of drivers might even hit the road works (see Fig. 7). Although the exact number might be slightly different when measured on the road, as compared to the prediction of our model, the consistency of the findings in the model give us high confidence in our main conclusion that 500 meter is not sufficient time to change lanes.

To prevent any accidents, the distance between the presentation of the in-car alert and the rumble strips needs to be around at least 620 m. Hence the warning distance needs to be 770 m (i.e., 620 + 150 after the rumble strips), since the warning is transmitted from the trailer, not from the rumble strip location. This contrasts with the way in-car signals can currently be implemented (cf. Gozálvez et al., 2012; Paier et al., 2010): on top of the first roadwork safety trailer (see introduction). Therefore, other alternatives need to be explored.

Different levels of cognitive load were used to see how lane change times varied with distraction (cf. Kunar et al., 2008; Strayer & Johnston, 2001). We found that the type of distraction significantly affected the initial reaction time to an in-car warning. These results are in line with previous work (Kunar et al., 2008; Strayer & Johnston, 2001). However, this previous work did not investigate how the impact of distraction continues after an initial reaction (i.e., after T1 in our study). We found that on average this difference did not persist in the total lane change time. This is most likely because the effect size of the differences between initial reaction times is small (300 ms) compared to the time that the entire lane change takes (around 4.2 s). The expected impact on everyday driving of this effect is hard to anticipate: being distracted mostly seems to impact initial reaction to a signal (in our study: time between T0 and T1, see Fig. 4). In cases where these delays are small (as in our study), later actions (e.g., between T1 and T2) might be able to compensate for some delays. However, this might not be the case if the initial reaction time is delayed severely.

6.1. Limitations and future work

Our study has investigated reaction time in the context of a visual warning and auditory distraction. In real traffic, in-car (visual) warnings might have been preceded by other external or internal warnings (e.g., road signs, or early warnings such as described in van der Heiden, Iqbal, & Janssen, 2017). Our work is meant to investigate what happens if the in-car warning is truly a last resort, which is one of the reasons such alerts are being designed. As the empirical and simulation results suggest, it might not be sufficient when a last resort warning is provided at 500 m distance from the road works. Future (empirical) work can study at how this changes when the signal is combined with other (on road or in-car) warnings. Moreover, such research could consider whether in these cases an additional signal might be confusing, conflicting, or distracting—for example, in cases where the driver has already changed lanes.

The in-car alert in our study was only visual. We chose this modality, as it is relatively less invasive compared to for example an audio alert (e.g., Cao, Castronovo, Mahr, & Müller, 2009). This is important for our context, as an alert by itself might also distract the user. Specifically, if a driver has already changed lanes, then a strong (audio) alert that indicates a lane change might confuse them. Future work should look into how different modalities of alerting affect lane change capabilities (e.g., cf. Spence & Ho, 2008). In general, reaction times to an audio signal are expected to be relatively short, as it is hard to overlook because audio signals are omni-present. Moreover, in contrast to a visual stimulus, auditory stimuli do not overlap with the visual requirements of the driving task and therefore interfere less with the driving task (cf. Wickens, 2002, 2008).

We found that there was no systematic effect of different levels of cognitive load on eventual lane change distance. This is due to the relatively small effect of initial reaction time. If a bigger sample of participants was used, or if the cognitive tasks

were even more demanding, a stronger lasting effect of the interfering task might have been found. Future work can explore how further methods of varying load affect performance.

6.2. Conclusion

In-car warnings as a last resort to prevent a crash might be helpful. However, our work shows that such warnings should be given timely. Even in a simple lane change set-up, a visual warning at 500 m before the incident is not sufficient for all drivers. It is therefore important to further consider whether and how technology can be used to provide such warnings in an even more timely fashion.

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