Blind flight: Do auditory lane departure warnings attract attention or actually guide action?

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ABSTRACT

This paper presents a research project concerning the effect of an auditory lane departure warning in a driving simulator experiment. The experimental design is chosen to induce drowsiness-related lane departures. We only evaluate situations where the driver is losing track because of moments of sleep. This design guarantees that the lane departures are unintentional and unconscious. Literature supports the point of view that the only effect of auditory lane departure warnings is to focus the driver's attention back onto the street and the steering reaction is a result of the driver's visual impression of the driving scene. We falsify this statement especially by measuring the time gap between the opening of the eyes after a warning and the steering reaction of the driver. If the reaction is based only on the visual impression, that duration can't be less than the minimum simple visual reaction time of 0.19 seconds.

1. INTRODUCTION

More than a dozen publications since 1995 deal with the human machine interface of lane departure warning systems, e.g. [1], [2], [3]. This kind of driver assistance system tries to prevent the driver from unintentionally leaving the road. This is a remarkable number of publications, considering the fact that only a few warning strategies seem reasonable. It is clear that a visual warning is not meaningful, because lane departures frequently happen in a state of drowsiness. Almost 25% of the deadly accidents in Germany happen as a consequence of drowsiness [4]. Hence it is unlikely that the drivers' eyes can be focused on a visual display, provided that the eyes are open at all. Alternative warnings use auditory or haptic signals. Both kinds of signals are able to attract the attention of the driver, difficult to ignore and are perceptible with closed eyes [5].

In one of the first studies, ZIEGLER ET AL. used a rumble strip noise as an auditory warning [1]. The efficiency of real-world rumble strips has been proven [6] and the idea is obvious: to use the sound of the rumble strips to warn the driver before the car reaches the lane border. Like auditory icons in other use cases, e.g. [7], [8], [9], the rumble strip noise should be an effective way to influence the driver's actions in a positive way. Additional information about the departure side offered by stereo sound is used to support this intuitive understanding: the warning occurs at the actual side of the lane departure (*directional warning*).

Considering haptic warnings - to ensure their perception - permanent contact points between car and driver are stimulated. Steering wheel torque and steering wheel vibration are mostly tested, e.g. [10], [11]. At present Citroën promotes a lane departure warning system with driver seat vibration as warning signal.

The result of comparing all the above publications is that none of these different warning strategies scores significantly better than the others. There are controversial results due to the technical implementation of the system and the different experimental designs. There is quite a difference between an abstract reaction task [3], a driving simulator study [12] and a field study [13]. But abstract tasks or driver simulator studies are necessary to evaluate lane departure warning systems with drowsy subjects, as it can hardly be done in a field study.

Another reason for the different results reported could lie in different states of mind of the driver. There is a substantial difference between a driver leaving the paved road in a moment of sleep [1] and one who is actively distracted, e.g. by a counting task [12]. In the first case the human mind "shuts down". The driver is not prepared to react to what happens next e.g. a warning sound. On the other hand there are advantages of distraction tasks, e.g. that every subject has controlled "lane departures" in an almost similar number, leading to a broad data base for statistical analysis.

However, we chose a more realistic way to induce lane departures in a driving simulator experiment as we tried to make our subjects tired and drowsy by stimulus deprivation. As a result, 15 from 31 subjects showed micro-sleep events while driving. The number of micro-sleep events greatly differed between the subjects. But this was only of secondary importance since we focused on single events, and analysed what happened when a driver felt asleep and woke up because of an auditory warning.

2. HYPOTHESES

Hypothesis 1: *The driver awakes by the sound of the warning signal. If the driver reacts according to nothing but the visual scene, the time between the opening of the eyes and his reaction can not be shorter than the general simple visual reaction time of 0.19 s as recorded for college students [14].*

SUZUKI stated that the only function of an auditory warning in lane departure situations is to attract attention [13]. The auditory warning wakes up the driver and focuses his attention back onto the street, but the steering reaction is initiated according to the visual analysis of the current driving situation. In his view auditory warnings attract attention, but do not guide action.

This statement based on video analysis of subjects in a driving simulator task. In the same study, SUZUKI showed that there are no differences in reaction time using directional and non-directional lane departure warnings [12]. These findings

hardened his assertion because a directional sound is not necessary to wake up the driver.
But if we find visual reaction times shorter than 0.19 s, the directional auditory signal must have triggered a specific kind of action. However, 0.19 s is a hard limit, considering statements in literature about a duration of 100-300 ms necessary for the process of perception, 300-400 ms for a steering decision and 30 ms to activate the muscles [3].

Hypothesis 2: T*here should be fewer situations with high reaction times and severe lane departures using a two-level warning*.

We believe that a two-level warning (a rumble strip noise followed by a bell tone, see section 3.3) is necessary to wake up drivers with a high sleep pressure. To verify this hypothesis, we performed a second, identical experiment using only a one-level warning. The one-level warning matches the rumble strip noise in the two-level warning.

3. METHOD

3.1. Participants

19 male subjects, age 22 to 27 years, participated in the first part of the experiment (*two-level-warning*), 12 male subjects of the same age group in the second part (*one-level warning*). All subjects were non-smokers, right-handed and most of them students at local universities. We paid 50 € for participation in the 5-6 hour experiment. The two samples included different numbers of subjects because of a limited time schedule and occurrence of driving simulator motion sickness.

Figure 1. *Split-screen picture showing the subject (top left), the driving scene (bottom left), the faceLAB-screen (top right) and the current driving parameters (bottom right).*

3.2. Apparatus

The experiment took place in a static driving simulator. The simulator scenarios were developed using the STISIM 500W commercial driving simulator software provided by Systems Technology Inc. [15]. The subject "drove" in a car mock-up in front of a 135° screen. Three projectors created a picture of the driving scenario and the whole experiment was documented on a digital video tape, see figure 1. Physiological data were recorded using a BioPac Systems, Inc. recording system. With a sample rate of 60 Hz a Seeing Machines stereo camera system together with the faceLAB-software tracked the eye movements and lid closures [14].

3.3. Stimuli

The first version of our auditory icon was a digital recording of a real-world rumble strip noise (recorded with binaural head microphones while driving). We asked a number of persons about the source of the recording, but no one mentioned the rumble strips. Therefore we started to create a rumble strip noise with an Absynth 2.0 software synthesizer (Native Instruments, Inc.). In a formative evaluation process [17] we asked different persons about the sound source again and afterwards about how to improve our rumble strip noise. The consequence was a continuous improvement process until only contradictory opinions were resolved (e.g. "pitch up" vs. "pitch down").
To ensure that our auditory warning signal was able to attract the driver's attention, we expanded the rumble strip noise by a second level auditory warning. When the lane departure warning system detected an upcoming lane departure a directional rumble strip noise was emitted from the same side. If the lane departure was avoided within 0.40 s the warning ended right at that moment. If the system still detected an upcoming lane departure after 0.40 s the second warning level started, containing a noise shift to the opposite side and ending up in a bell tone, see figure 2. This warning design was based on some results about the Simon Effect [18] and on LEWIN's theory about positive and negative valence [19]. But its main reason was to insure the attraction of attention. Therefore, the bell tone was louder (77.8 dB(A)) and more intensive than the rumble strip noise (68.6 dB(A)) measured at the driver's ears. The loudness of the warning signal was adjusted according to the feedback of the subjects in the pilot trials.

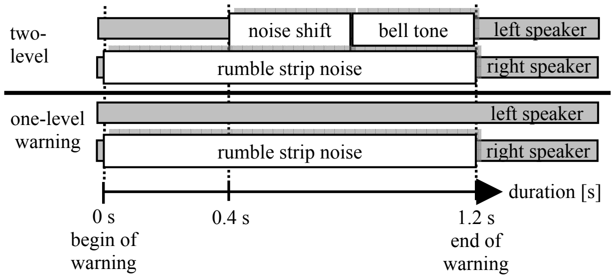

Figure 2. *Schematic example of a one- and two-level warning sound at the moment of a right lane departure.*

3.4. Procedure

The subjects' task was to drive in the simulator for about 2.5 hours. They received no information about the real objective of the experiment. We told them instead that we wanted to test our improved driving simulator. The subjects were requested to stop the drive immediately when feeling sick.
At the beginning of the experiment each subject was asked about his physical and emotional state using the MBDF questionnaire [20]. A 20 to 25 minutes test drive followed. Then there was a lunch break, after which the physiological sensors were placed on the subjects' body. Right before the experimental drive a paper-and-pencil concentration test (d2-Test, [21]) had to be filled. The experimental drive started around 1:30 p.m. We tried to use that period of the human circadian rhythm in which our body and mind performance

show an early afternoon drowsiness feeling. We reinforced this effect by designing a special "stimuli deprived" driving scenario. The subject drove in a foggy landscape for about 2 hours with a speed limit of 50 km/h. Only few other cars appeared in this scenario and the track was easy. Most of the possibilities of self-activation were not available (e.g. mobile phone, wrist watch).

The whole scenario had a length of about 134 km, subdivided in four parts. The "Baseline"-part was 6 km long, easy to drive and without traffic, followed by the "Control"-part, which was repeated at the end of the scenario. For about 9.1 km the driver had to cope with high density traffic, difficult curves and various landscapes. Then the stimuli deprived drowsiness induction part followed. It consisted of six identical repetitions (6 x 18 km, see figure 3). There was fog (approximately 50 m range of vision) and the traffic was reduced to a minimum. With the exception of a single difficult curve, all curves were easy. During the whole fog scenario the speed was limited to 50 km/h. It was our intention to induce fatigue in our subjects by deprivation of stimuli. The experimental drive finished with the "Test"-part (the repetition of the "Control"-part). We used it to detect changes in driving behavior after 2 hours of deprivation of stimuli.

After the experimental drive the subject filled the MBDF questionnaire and the d2-test again. A questionnaire about the auditory warning style concluded the trial.

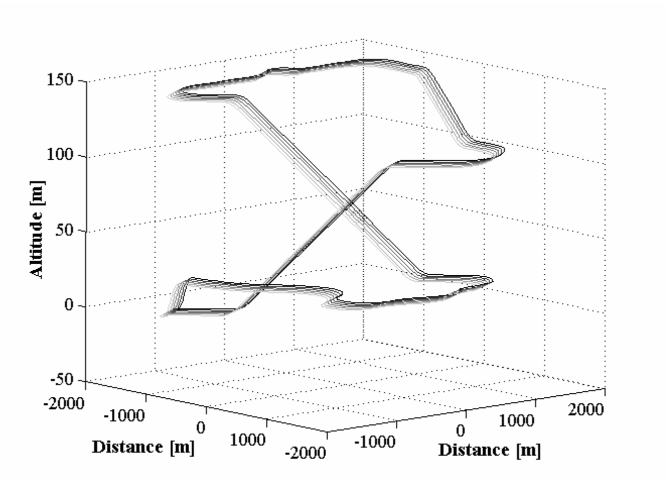

Figure 3. *Three-dimensional trace. The black lines indicate the six "Deprivation of stimuli"-parts of the scenario. The distance is expressed on the horizontal axes, the altitude on the vertical axis [22]).*

4. RESULTS

4.1. Categorization

We performed a video examination of the entire 1430 lane departure warnings (one-level warnings: 617, two-level warnings: 813) and sorted the events into different categories according to the situation. There were situations in which the driver left his lane intentionally, e.g. by curve cutting (*driving related lane departure*). Then there were moments of sleep leading to a lane departure (*sleep related lane departure*). But sometimes it was hard to decide if the driver really felt asleep. In cases of uncertainty, we categorized such situations together with lane departures based on inattention (*inattention related lane departure)*. There had to be clear signs of moments of sleep, e.g. upturning iris, to justify a categorization as *sleep related*. Very few warnings appeared meaningless to the driver and seemed due to system failures. If we hold the same opinion, we categorize such situations as *system errors*.

This categorization was double-checked by an independent person, rating 10% randomly chosen lane departure warning situations. The measurement of agreement between the two ratings was done by the κ-statistic. A κ-value of 0.715 indicated a good agreement between both raters [23].

4.2. Hypothesis 1: Visual reaction time [s]

To falsify this hypothesis we only used the data from the experiment with the two-level warning. In the experiment with the one-level warning the faceLAB-System was absent, so we could not measure the duration of eye-lid closure.

According to our categorization 373 *driving related lane departures,* 180 *sleep related lane departures* (SRLD), 237 *inattention related lane departures* and 23 *system errors* occurred in the two-level warning experiment. 8 subjects had SRLDs. The individual number of SRLDs differed greatly between subjects, ranging from 1 to 75.

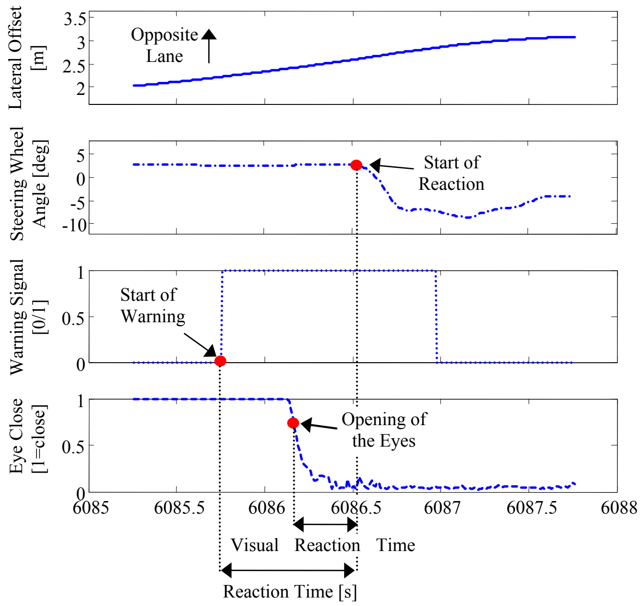

Figure 4. *Lane departure warning situation including overall reaction time and visual reaction time.*

We then concentrated on the 180 SRLDs and calculated the reaction time associated with each of them. The **reaction time** is defined as the time gap between the beginning of the warning and the first change in the steering angle passing a threshold of 1°, see figure 4. The 1°-threshold was necessary to exclude "involuntary movements", because it is almost impossible to keep the steering wheel perfectly still while driving. Using this criterion we weren't able to calculate the reaction times of 9 SRLDs because no steering reaction bigger than 1° happened in a 10 s period after the warning. 21 reaction times yielding values below 0.16 s were excluded from the list as well. This threshold is the minimum simple auditory reaction time for college students [14] and shorter reaction times are considered non-physiological and do not represent an actual reaction to a stimulus. Our conclusion is supported by the faceLAB data, showing that almost every reaction time under 0.16 s could be explained with open eyes some milliseconds before the warning sounds.

Reaction times over 2 s were excluded as well. They fulfilled an extreme value criterion: 5 values could be thus excluded, because they were more than 3 interquartile ranges away from the first or third quartile [24].

At last we checked our data concerning lid closure. We wanted to be sure that all SRLD warnings took place with closed eyes. At the end of the exclusion process there are still 77 SRLDs left from two subjects: 23 SRLDs occurred during the drive of subject 11, 54 from subject 13. For all 77 SRLDs we calculated the **visual reaction time**. It represents the time gap between the opening of the eyes for at least 25% of the iris and the instant of the steering reaction of the driver, see figure 4. The threshold of 25% is used by the faceLAB PERCLOS-algorithm to identify lid closure [16]. Our hypothesis states that visual reaction times of 0.19 s and below cannot occur or are not fully explainable with a visually triggered action alone. However, the data show 35 events with "too quick" reaction times (QRs). Subject 11 performed 8 QRs, subject 13 performed 27 QRs, see figure 5 (white squares). The distribution of the QR-warnings in each of the subjects' own drive indicates that there is no pattern of appearance except, that subject 11 has QRs all over the scenario but not within the last 20 minutes of this drive.

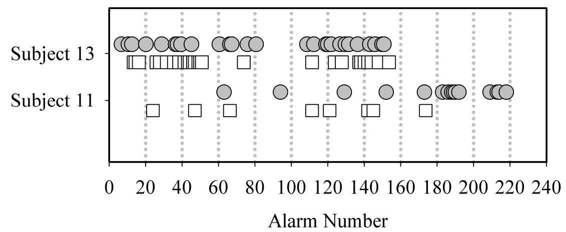

Figure 5. *Sleep related lane departure alarms displayed by subject and in order of appearance. Alarms with visual reaction times of 0.19 s and below are marked with white squares. Alarms with visual reaction times above 0.19 s are marked with grey circles.*

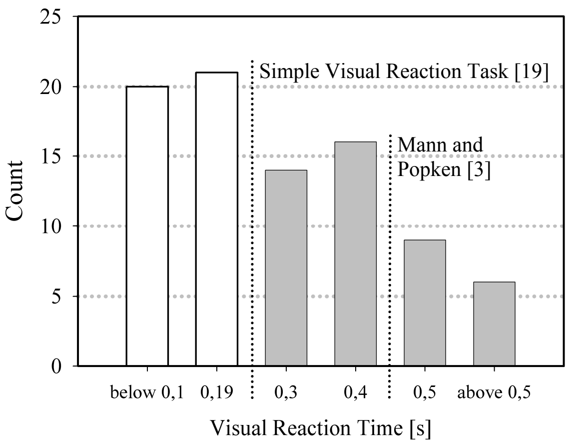

Figure 6. *Distribution of the measured visual reaction times. The values on the x-axis indicate the borders of the categories. Visual reaction times under 0.19 s are displayed in white bars, visual reaction times above 0.19 s in grey bars. The dotted vertical lines indicate visual reaction times published by other authors.*

However, it is hard to show a correct steering reaction within 0.19 s. Maybe the time limit that defines QR-warnings is therefore too short. Looking at the frequencies of the response time values of the SRLDs we found that with a weaker time limit much more reaction times have to be judged as QRs, see figure 6. Using a time limit of 0.4 s 51 from 77 SRLDs, had to be judged as QRs.

A possible explanation for the QRs is that they happened because of haste and carried out randomly sometimes in the correct and sometimes in the wrong direction. This would yield an even distribution of correct and wrong reactions. Instead, we found subject 11 having 22 correct and only one incorrect reaction. The incorrect one happened with a QR. Subject 13 showed 45 correct reactions and 9 wrong reactions. 6 of the 9 wrong responses happened with a QR, see figure 7.

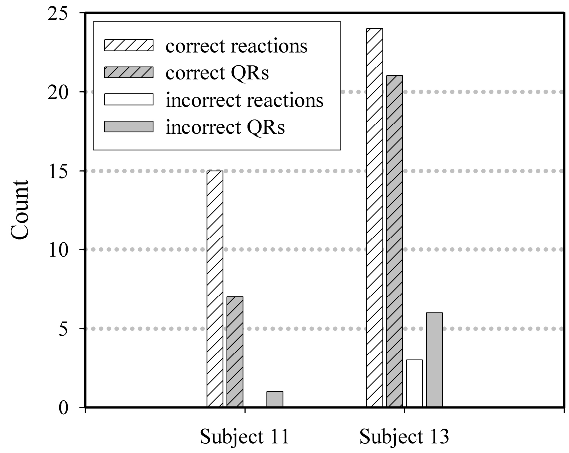

Figure 7. *Sleep related lane departure warnings from subject 11 and subject 13. White bars indicate the number of warnings with normal visual reaction time, grey bars the number of warnings with a too quick visual reaction time. Hatched bars indicate correct steering reactions, solid bars incorrect steering reactions.*

We wanted to find out if there is a positive coherence between an incorrect steering reaction and a QR. Therefore we used a Fisher Exact Test [25]. The result indicated that there is no coherence between the two variables, $\chi^2(1)=1.179$, $p=0.229$. This is still not a final evidence for the positive influence of our auditory warning signal on steering reaction, but at least we can show that there are visual reaction times shorter than expected and this not by chance.

4.3. Hypothesis 2: Auditory reaction time [s] and absolute lane departure [cm]

After the first part of our experiment, we wanted to know if the mean reaction time is the same using a one-level warning (only rumble strip noise). Unfortunately this time it wasn't possible to use the eye-tracking system in the protocol of our experiment. Because of that, the following analysis was done based on the SRLD judgments from our video examination. SRLDs with reaction times under 0.16 s and above 2 s were excluded as before.

There were 8 subjects with 145 SRLDs in the two-level warning experiment as described before. The average reaction time calculated over all warnings was 0.64 s (SD=0.35 s). It seemed plausible to use the average over all warnings rather to use the mean value of the average reaction time of each subject. Otherwise, the only available reaction time of subject 10 had much more influence on the mean reaction time than the 76 reaction times of subject 11. As mentioned before, the problem was that the moments of sleep differed between the subjects from 1 to 75.

Doing the same experiment with a one-level warning we got 156 SRLDs. 7 subjects had moments of sleep, differing from 1 to 125 SRLDs. The average reaction time calculated over all warnings was 0.44 s (SD=0.17 s). That was not what we had expected, assuming that our two-level warning would reduce reaction time.

We used a nonparametric Mann-Whitney-U-Test [25] to compare the means of both samples, because the data of both samples didn't fit to a normal distribution, the homogeneity of variances was not given and the samples didn't have the same size. The test showed a significant difference between the reaction times of the one-level warning and the two-level warning, U=7251, p<0.001.

To interpret that results we used the questionnaire the subjects had to fill right after the experiment. The answers allowed some explanations. The two-level warning seemed to be too complex and therefore irritating, or too intensive and therefore startling. However, the incorrect steering wheel reactions in both samples were almost equal: 14 with two-level warning and 11 with one-level warning. A χ^2-Test was done to check if there is a significant difference between the frequencies of an incorrect steering reaction using a one-level or a two-level warning. The frequencies were not significantly different, $\chi^2(1)=1.2124$, p>0.25. In general, 37% of the subjects with two-level warning preferred such a kind of warning strategy and even 42% of the subjects with one-level warning thought that a two-level warning would be a good idea.

At last we looked at the absolute lane departure. This value gives information about how many centimetres the car outer wheels are outside the lane border. In Table 1 we listed how many lane departures larger than 0 cm happened when a warning occurred.

Table 1. Number of absolute lane departures larger than 0 cm for each treatment.

		Absolute Number of Lane Departures		
		0 cm	**> 0 cm**	Total
Treatment	**two-level warning**	81	64	145
	one-level warning	94	62	156
	Total	175	126	301

The differences between the two-level warning and the one-level warning are small. A χ^2-Test shows no significant effect of treatment on the absolute number of lane departures larger than 0 cm, $\chi^2(1)=0{,}596$, p>0.5.

We did a Mann-Whitney-U-Test [25] to focus not only on the number of lane departures larger than 0 cm, but also on their absolute values. There are 64 departures with a two-level warning having an average departure of 51.38 cm (SD=60.92 cm). The 62 lane departures with a one-level warning have a mean of 48.87 cm (SD=78.54 cm), see figure Figure 8. The U-Test indicates no significant difference between both treatments; U=1761, p=0.277.

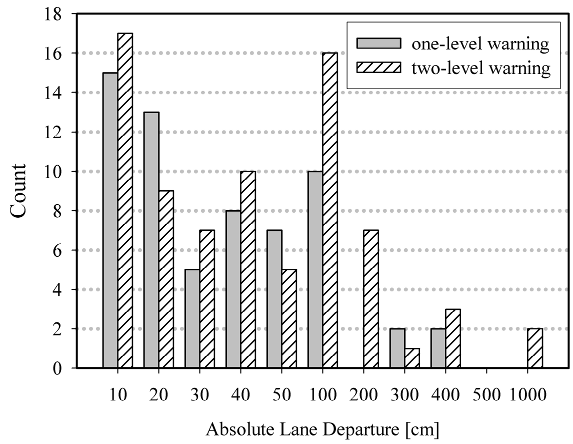

Figure 8. *Number of absolute lane departures in centimetre-categories separated by treatment.*

5. CONCLUSIONS

In the study described in this paper we observed what happened when a driver in a driving simulator experiment fell asleep and was woken up by a lane departure warning system.

First, there were indications that auditory warnings can influence human actions and not only act as a wake-up call. We showed that there are steering reactions too fast to be initiated by the visual impression of the driving scene alone. Video observation and statements of the subjects supported two explanations: priming [26] and/or learning processes. The directional auditory warning sometimes acted as a prime, directing the attention and behavior to a specific side and preparing the action. Some subjects mentioned that they learned about the meaning of the auditory signal and were able to act according to the directional auditory warning before they have to look on the driving scene. If that is true, positive learning effects appeared fast. Subject 13 showed such quick reactions already the 7th time he heard the auditory warning. Positive influences of three-dimensional auditory warnings on human responses have been shown already [27].

We tried to design a rumble strip noise and connect it with an intensive bell tone. The bell tone should wake up all those drivers who haven't been woken up already by the rumble strip noise. Therefore, we expected a lower reaction time compared to the one-level rumble strip noise. But the opposite was true: the one-level rumble strip warning caused a significantly lower mean reaction time. But no significant difference in the absolute magnitude of lane departure could be found. Statements of the subjects indicated that the two-level warning was too complex and hard to understand, so that the driver needs to get used to it. Furthermore, they mentioned the high intensity of the second-level warning tone, which could lead to irritation and startle effects. Last, the answer may consist in habituation processes. The two-level warning occurred not only in critical situations. The driver heard it in non-critical situations of lane departure, too. So some drivers got used to it and the second level alarm lost its effectiveness [28]. In a future experiment we will tackle some of the new questions we have raised here.

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