Spatially distributed visual, auditory and multimodal warning signals – a comparison

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Abstract

Spatially distributed warning signals are able to increase the effectiveness of Advanced Driver Assistance Systems. They provide a better performance regarding attention shifts towards critical objects, and thus, lower a driver’s reaction time and increase traffic safety. The question which modality is used best, however, remains open. We present three driving simulator studies (30 participants each) with spatially distributed warnings, whereby two focused on spatial-visual as well as auditory warnings respectively. The third study, which combined the most promising approaches from the previous studies, depicts a multimodal spatial warning system. All studies included a baseline without secondary tasks and warnings. Afterwards, subjects were confronted with multiple (30+) critical objects while performing a secondary task. The chronological order of warnings was randomly mixed between spatial, non-spatial and no warning during the first two studies. Data from reaction times, eye tracking data, and questionnaires were collected. Results show that spatial-visual directed warnings are more effective than non-spatial warnings in large distances, but subjects do have difficulties in detecting objects in peripheral regions when they are distracted. While auditory spatial warnings are not as efficient as literature implies, it still performed best in this particular situation. Results of the multimodal warning study, discussion and implications on Advanced Driver Assistance Systems (ADAS) conclude the paper.

Introduction

In 2015 2,516,831 people were involved in traffic accidents (German Federal Statistical Office, 2015). In relation to that 305,659 people were injured and 3,459 died. That was an increase of +1.1% to the prior year. Human errors while driving were the main reason for accidents (68.8%). They were either distracted, ignored traffic regulations, made mistakes at turning manoeuvres, or failed to keep an appropriate safety distance to vehicles driving ahead. This behaviour is the consequence of human errors in perception and cognition of information and responding appropriately in such situations (Bubb, 1993; Spanner-Ulmer, 2008). Lee (2008) concluded that accidents happen when the driver fails to look at the right time at the right object. Posner (1980) stated that by means of spatial cues a faster reaction towards spatial stimuli is possible.
Using such spatially directed cues in Advanced Driver Assistance Systems (ADAS) can help to support drivers in these domains (Jentsch, 2012) by directly focusing (or shifting) the attention towards hazardous objects. In that way the risk potential for distracted drivers can be minimised. Possible warning signs could be visual or auditory cues. Spatially directed visual cues are able to shift the driver’s attention towards relevant objects using a novel Head-Up-Display (HUD) based on light emitting diodes (LED) mounted underneath the windscreen. This can result in lower reaction times and benefits the overall quality of reaction in critical situations (Dettmann et al., 2014). Due to technical limitations there might be restrictions when presenting optical warning signals with LED-HUD in the peripheral field of vision (e.g. driver is looking to the right and the spatial-visual cue is on the left outside of the HUD). To help to counteract the problematic of warning perception in the peripheral visual field a second warning modality, auditory cues are promising. Similar to the visual warning there are also two presentation modes possible: a conventional, undirected auditory warning signal and a spatially directed auditory warning signal. They seem to be a beneficial integration as audible cues are generally more efficient in shifting attention compared to visual cues (Proctor et al., 2005; Scott & Gray 2008; Haas & van Erp 2014). Using spatially directed sound is based on the assumption that selective spatial attention can improve cognition (Lampar, 2011; Haas & van Erp 2014).

To examine the concept and the effectiveness of spatially directed cues for each visual and auditory warning modality, we undertook two driving simulator studies. The first using visual warnings (spatially directed and undirected) by means of the LED-HUD and a second study using solely auditory warnings in the same manner. The main focus was to investigate the impact of the warning concepts on reaction times. Auditory and visual cues were then compared and glance behaviour was analysed depending on the warning modality (auditory vs. visual). The following third study embraced the most promising approaches from the previous studies towards a combined multimodal warning. This approach was taken, as it was the intention to examine the distinct effects and limitations of each spatially distributed visual and auditory warning modality on drivers’ perception. The third study primarily evaluates the overall concept of a spatial warning system using a novel LED-HUD.

The present paper initially describes the realisation of visual and auditory directed cues, including the underlying warning concept, followed by the description of the simulator study and the representation of results for each study. This also includes the results of a sector based analysis of where potentially dangerous objects appeared (near/far, inside/outside, left/right). Discussion and implications on Advanced Driver Assistance Systems with spatial warning signals will conclude the paper.

**Realisation of spatially directed warning cues**

For the realisation of the visual warning an LED-HUD connected to the driving simulator was used. The used LED-HUD can be regarded as a multifunctional human-machine-interface for advanced driver assistance systems or in-vehicle information systems applicable for collision warnings (Lindner et al., 2009),
spatially distributed warning sign

attentional control (Kienast et al., 2008) or as an assistant system for autonomous driving. The LED-Panel is built as a 135° circle segment mounted underneath the windscreen. It is able to cover 50° of the driver’s field of view. It consists of nine panels each with 256 LEDs and is able to display spatially directed optical warnings. These can either be semantically enriched pictograms (e.g. direction, distance or object types) or simple flashes. Both signal types can be presented on the LED-HUD towards the position of a potentially dangerous object. For the present studies a white flashing square was used as shown in figure 1. This warning concept was evaluated in a prior study by Pöschel et al. (2013). Ten experts compared symbols representing different types of objects (e.g. car or pedestrian) or information (e.g. traffic signs).

![Figure 1. Warning concept on the LED-HUD](image)

Despite the low semantic information, the symbol was favoured because of its high contrast and the possibility to implement high blinking frequencies (e.g. flashes) which are particularly useful in peripheral regions as they are highly sensitive for flicker (Mühlstedt, 2013). The used flash was visible for 250 ms long in a 0.4 s cycle.

The auditory warning used in the second study was developed based on the guidelines of design principles for auditory warnings and were tested in the driving simulator (Wogalter & Leonard, 1999; DIN EN ISO 15006, 2011). Four experts evaluated issues concerning volume and speaker position. The four point audio system in the simulator was positioned in a way that hearing and detecting the direction of audible cues was possible which was also tested and approved by the expert group. The audio signal had a base frequency of 2,573 Hz and was 60 dB loud and contained four repeated single tones.

A multimodal approach was examined for the third study. The same LED-HUD and warning was used (spatially directed visual warning) as well as the presented auditory signal (conventional warning design, undirected).

**Method**

To examine the effectiveness of spatially directed cues, two conditions were presented to the subjects: first, a spatially directed cue oriented towards an object (occurring stationary vehicle; see figure 2, right), whereas the second condition was the conventional, undirected cue where the alert occurs in the middle (figure 2, left). A “no cue” condition was equally presented in the first study to examine the general effectiveness of warning signals. Each participant underwent both conditions in balanced order while being distracted by a secondary task. The third study with the
multimodal warning design contained only one warning condition. To distract the participants from driving, i.e. looking at the street, a secondary task was used, consisting of moving geometric figures. The underlying concept is to recreate a situation where the driver is not aware of his situation and possible hazardous objects. Therefore, the overall effectiveness of each warning modality can be evaluated free of any confounding variables. The subjects were asked to recognise size, length or colour features and report their answer to the experimenter. The secondary task was meant to be a contrary cue with no relationship to the primary driving task (Schweigert, 2012). Before the actual experiment, all subjects completed a familiarisation and a baseline drive. The baseline drive excluded the secondary task to measure the reaction times when the driver was not distracted.

All studies were conducted on a simulated straight test track measuring 5000m by 150m without any traffic. The goal was to minimise any possible distractions caused by the environment or traffic.

While driving, 32 static objects were presented to the subjects. They appeared in random intervals of 5 – 10 s at a recommended speed of 50 km/h. The distance between the driver and the object was randomised from 40m to 200m. Furthermore, the point of occurrence varied between eight sections. These sections consisted of four horizontal sections divided into close and long-range sectors. Distances up to 100m from the subject represented the close range, while distances from 120m upwards formed the far range. No objects were presented at distances from 100m to 120m to achieve a higher separation effect. Objects along the lane were mirrored and up scaled to the right side due to a wider opening angle of the windscreen on the right. Objects became smaller and less noticeable at larger distances.
To measure the quality of the warning signals (e.g. reaction time), participants were requested to press a button on the steering wheel as soon as they detected the object (either the left button when the object occurred on the left side or the right button when it occurred on the right). Correct responses were followed by some visual and audible feedback as the object disappeared when the correct button had been pressed. Also, a distinct signal tone different from the warning signal gave feedback. The experiment was conducted as a within-subjects design. To measure the reaction times driving data was gathered (simulator software SILAB 4.0). This data includes time markers for object appearance and button actuation. The reaction time is defined as the difference between the occurrence of the objects and the moment when the participants pressed the button on their steering wheel. Therefore, the difference between those markers was calculated. Additionally, eye-tracking data (system Dikablis) was gathered to control in which direction the subjects were looking in the moment of the objects appearance. This was done by comparing the time stamps of the driving and the eye-tracking data and then looking at the glance direction of the subjects.

To ensure comparable reaction times the data points had to meet the following criteria: A data point is valid if (1) participants looked at the secondary task at the time the object occurred, (2) the object was perceived and the correct steering wheel button was pressed and (3) the buttons on the steering wheel worked perfectly. All studies combined a total of 2157 valid data points collected from 90 participants who were distracted by a secondary task. This results in an average of 719 valid data points (76.7 %) for each study. The most common reason for non-valid data points was the participants’ attention which was not centred at the secondary task (19.7 %). The value 1.9 % resulted from pressing the button on the wrong side of the steering wheel. 1.7 % was caused by technical problems with the buttons on the steering wheel. Non-valid data points were excluded from the calculations and, therefore, had no influence on the results. Table 1 gives an overview of the valid data points for each study.

Figure 3. Distribution and position of potentially critical objects in eight sectors
Table 1. Overview of valid samples

<table>
<thead>
<tr>
<th>STUDY</th>
<th>Valid samples [N]</th>
<th>Not processes secondary task [%]</th>
<th>Problems with buttons [%]</th>
<th>Wrong reaction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>695</td>
<td>20.2</td>
<td>5.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Auditory</td>
<td>722</td>
<td>19.8</td>
<td>0.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Multimodal</td>
<td>740</td>
<td>19.1</td>
<td>0.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Overall average</td>
<td>721.3</td>
<td>19.7</td>
<td>1.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

For all valid data points a sector based and a field based analysis (near/far, inside/outside, left/right) was conducted to get better insights of how effective each warning modality in certain areas performs. Figure 4 gives an overview of where the sectors are located.

![Figure 4. Location of each zone for the sector based analysis](image)

Additionally, in all studies the participants were to answer non-validated questionnaires helping to evaluate their current mental condition (five-point Likert items: excited/nervous, awake/tired), system acceptance (intention to buy), sociodemographic data (age, gender, visual and hearing performance) as well as the design of the cues (five-point Likert items: e.g. urgency, locatability, aggressiveness).

**Sample**

Participants of all three simulator studies were matched for age and gender being comparable to the sample of Dettmann et al. (2014). Each study counted 30 participants aged from 19 to 45 ($M_{age} = 28.7, SD_{age} = 6.3$), whereby 36.7 % were female. All participants owned a valid driving licence and drove an average of 11,063 km per year. The mean age of the sample was equivalent to Dettmann et al. (2014). Significant differences were only found in annual mileage (analysis of variance (ANOVA), $F(2, 55) = 3.972, p = .022$) whereas the “auditory” and the
“multimodal” group hold significantly fewer driven kilometres per year than the “visual” group.

Table 2. Overview of the participants

<table>
<thead>
<tr>
<th>STUDY</th>
<th>#</th>
<th>M_age</th>
<th>SD_age</th>
<th>M_annual_km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>30</td>
<td>30.4</td>
<td>7.6</td>
<td>18,133</td>
</tr>
<tr>
<td>Auditory</td>
<td>30</td>
<td>28.9</td>
<td>4.8</td>
<td>8,661</td>
</tr>
<tr>
<td>Multimodal</td>
<td>30</td>
<td>26.9</td>
<td>6.0</td>
<td>9,021</td>
</tr>
</tbody>
</table>

Results

For all studies the influence of the mental condition on valid data points can be neglected. There was no relationship found between the drivers’ condition (excited/nervous, chi-squared test: \( \chi^2(3, N = 2820) = 4.87, p = .18 \)) and the percentage of valid data points. The same applies for the condition “awake/tired” (\( \chi^2(4, N = 2820) = 2.96, p = .56 \)). For all ANOVA conducted, the Levine’s Test for Homogeneity of Variance met the assumption of equality of variances.

Comparison of visual warning conditions and no warning

For the sector based analysis of the reaction times for the visual warnings a single factor variance analyses was carried out. To examine the overall effectiveness of the LED-HUD all visual warnings (directed and undirected) were compared with the “no warning” condition. This resulted in significant lower reaction times for the warning condition in the sectors W1-W4 (see table 3). For close objects (sectors N1-N4) only for sector N2 a significant difference was found between all directed and undirected visual warnings and the “no warning” condition.

- W1 ANOVA, F(2, 83) = 32.938, p < .001
- W2 ANOVA, F(2, 89) = 60.976, p < .001
- W3 ANOVA, F(2, 82) = 23.469, p < .001
- W4 ANOVA, F(2, 97) = 32.469, p < .001
- N2 ANOVA, F(2, 61) = 6.467, p = .003

In sector W2 a significant difference between the directed and undirected warning was found (post hoc analysis (Scheffé’s method) \( p = .034 \)) while in sector W4 only a mild trend was found (post hoc analysis (Scheffé’s method) \( p = .088 \)). This applies to the sector N3 as well (ANOVA, \( F(2, 65) = 4.509, p = .015 \)). Through the post hoc analysis also a trend between directed and undirected warning was found (Scheffé’s method \( p = .093 \)). The reaction times for all three conditions are presented in table 3 and figure 5.
Table 3. Overview of the reaction times for the visual warnings

<table>
<thead>
<tr>
<th>Visual warning</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatially directed</td>
<td>$M$</td>
<td>1.41</td>
<td>1.11</td>
<td>1.23</td>
<td>1.25</td>
<td>1.08</td>
<td>1.12</td>
<td>0.91</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>$SD$</td>
<td>0.44</td>
<td>0.37</td>
<td>0.41</td>
<td>0.30</td>
<td>0.36</td>
<td>0.54</td>
<td>0.22</td>
<td>0.27</td>
</tr>
<tr>
<td>Spatially undirected</td>
<td>$M$</td>
<td>1.24</td>
<td>1.64</td>
<td>1.59</td>
<td>1.66</td>
<td>1.05</td>
<td>0.92</td>
<td>1.22</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>$SD$</td>
<td>0.53</td>
<td>0.75</td>
<td>0.70</td>
<td>0.68</td>
<td>0.36</td>
<td>0.38</td>
<td>0.46</td>
<td>0.27</td>
</tr>
<tr>
<td>Baseline</td>
<td>$M$</td>
<td>2.47</td>
<td>3.60</td>
<td>3.36</td>
<td>2.87</td>
<td>1.10</td>
<td>1.56</td>
<td>1.33</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>$SD$</td>
<td>0.78</td>
<td>1.21</td>
<td>1.84</td>
<td>1.08</td>
<td>0.46</td>
<td>0.76</td>
<td>0.66</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 5. Reaction times for the visual warning

When combining the sectors into fields (near/far) and (left/right) only for near and far fields significant differences were found:

- near ANOVA, $F(2, 325) = 6.890$, $p = .001$
- far ANOVA, $F(2, 360) = 116.834$, $p < .001$

The post hoc analysis showed no differences for the near sectors, but for the far sectors: directed ($M = 1.25$ s; $SD = 0.39$ s) and undirected ($M = 1.59$ s; $SD = 0.7$ s) warning ($p = .024$). Regarding the left and right fields also significant differences were found:

- left ANOVA, $F(2, 333) = 58.287$, $p < .001$
- right ANOVA, $F(2, 352) = 46.940$, $p < .001$

While there is no difference between directed and undirected warnings to the left, on the right side a significant difference between directed ($M = 1.07$ s; $SD = 0.32$ s) and undirected ($M = 1.44$ s; $SD = 0.64$ s) warnings ($p = .014$) was found.
From the questionnaires it was found, that 21 out of 30 subjects rated the directed visual warnings as very supportive. Only seven rated the undirected warnings more useful and two subjects found that they felt no support from the warnings. Figure 5 is showing three additional subjective ratings to characterise directed or undirected warnings on a five-point Likert scale.

Comparison of auditory warning conditions

For the second study the same sector and field based analysis (see figure 4) was carried out. Overall no significant differences between directed and undirected warnings were found ($t(720) = 1.71, p = .088$). Significant differences between directed and undirected warnings were found in the sectors W3 ($t$-test $p < .001$), N4 ($p < .001$) and N1 ($p < .001$). For the sectors W3 and N4 undirected auditory warnings performed better and for sector N1 directed warnings showed faster reaction times. All reaction times regarding auditory warnings are shown in table 4 and figure 7.

Table 4. Overview of the reaction times for the auditory warnings

<table>
<thead>
<tr>
<th>Auditory warning</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatially directed</td>
<td>$M$</td>
<td>1.01</td>
<td>1.19</td>
<td>1.48</td>
<td>1.40</td>
<td>0.91</td>
<td>0.9</td>
<td>0.93</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>$SD$</td>
<td>0.34</td>
<td>0.62</td>
<td>0.49</td>
<td>0.71</td>
<td>0.23</td>
<td>0.32</td>
<td>0.43</td>
<td>0.32</td>
</tr>
<tr>
<td>Spatially undirected</td>
<td>$M$</td>
<td>0.99</td>
<td>1.11</td>
<td>1.10</td>
<td>1.22</td>
<td>1.33</td>
<td>0.92</td>
<td>0.93</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>$SD$</td>
<td>0.34</td>
<td>0.43</td>
<td>0.36</td>
<td>0.57</td>
<td>0.24</td>
<td>0.35</td>
<td>0.43</td>
<td>0.26</td>
</tr>
</tbody>
</table>

When analysing the fields (near/far), (inside/outside) and (left/right) significant differences for the far sectors were found (ANOVA, $F(3, 198) = 8.371, p = .000$). The undirected warning signals ($M = 1.10 \text{ s}, SD = 0.44 \text{ s}$) were more efficient than directed signals ($M = 1.26 \text{ s}, SD = 0.59 \text{ s}$). For the combined left and right sectors inconsistent results were found. On the left directed auditory warnings worked better (ANOVA, $F(1,364) = 3.964, p = .047$; directed: $M = 1.01 \text{ s}, SD = 0.43 \text{ s}$; undirected: $M = 1.09 \text{ s}, SD = 0.38 \text{ s}$) and for the right side undirected auditory warning signals had significant lower reaction times: ANOVA, $F(1,356) = 15.633, p < .01$; directed: $M = 1.22 \text{ s}, SD = 0.53 \text{ s}$; undirected: $M = 1.02 \text{ s}, SD = 0.44 \text{ s}$. No difference were found for the (inside/outside) fields. Figure 8 is showing three subjective ratings to characterise directed or undirected auditory warnings on a five-point Likert scale.
Results of the multimodal study

In the third study only one condition, the multimodal approach, was examined. The warning design embraced the most promising approaches (visual directed and auditory undirected) from the previous studies towards a combined multimodal warning. The single factor variance analyses reports no differences between each sector ($F(2, 7) = 24.8, \ p < .001$). The comparison between all three conditions is showing that the multimodal warnings are performing significantly better across all sectors. Table 5 and figure 9 are giving an overview of the multimodal reaction times compared to the visual directed and auditory undirected warnings and their respective reaction times.
Table 5. Overview of the all reaction times

<table>
<thead>
<tr>
<th>STUDY</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatially directed visual</td>
<td>M</td>
<td>1.41</td>
<td>1.11</td>
<td>1.23</td>
<td>1.25</td>
<td>1.08</td>
<td>1.12</td>
<td>0.91</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.44</td>
<td>0.37</td>
<td>0.41</td>
<td>0.3</td>
<td>0.36</td>
<td>0.54</td>
<td>0.22</td>
<td>0.27</td>
</tr>
<tr>
<td>Conventional auditory</td>
<td>M</td>
<td>0.99</td>
<td>1.11</td>
<td>1.10</td>
<td>1.22</td>
<td>1.33</td>
<td>0.92</td>
<td>0.93</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.34</td>
<td>0.43</td>
<td>0.36</td>
<td>0.57</td>
<td>0.34</td>
<td>0.35</td>
<td>0.43</td>
<td>0.26</td>
</tr>
<tr>
<td>Multimodal</td>
<td>M</td>
<td>0.76</td>
<td>0.78</td>
<td>0.78</td>
<td>0.77</td>
<td>0.76</td>
<td>0.76</td>
<td>0.74</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.31</td>
<td>0.2</td>
<td>0.18</td>
<td>0.16</td>
<td>0.22</td>
<td>0.29</td>
<td>0.14</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Figure 9. Reaction times for all three conditions

Discussion

In accordance with other research works (Fricke, 2009; Scott & Gray, 2008) the present experiment compared reaction times with and without warning. In general the efficiency of warnings can be confirmed repeatedly. Visual warnings represented on a LED-HUD as used in the first experiment are suitable for shifting back the attention to objects on the roads when the driver is distracted. Especially spatially directed visual warnings are helping to shift the attention towards relevant objects in road transport quickly and intuitively. Best results were found for object detection and reaction in far-distant sectors (W2 – W4). If the spatial directed warning is displayed far left (e.g. in sector W1) it becomes disadvantageous as the driver may not recognise the warning signals. The processing of the secondary task and the resulting orientation to the right an increased effectiveness of the directed warning compared to the undirected warning could not be proved. This is also true for all near-field areas. Regarding the questionnaires, it also becomes apparent that the directed warning signals were rated more useful than undirected warnings. Subjects
find, that the directed warning is more supportive in shifting the attention and provides a faster reaction.

For the second study, it was assumed that spatially auditory warnings are able to increase the effectiveness in peripheral regions as acoustical spatial stimuli are omnidirectional and no fixation is needed. It was found that this is true for far-distant sectors (W1) but not for near peripheral sectors (N1). Overall no consistent results regarding reaction times were found that spatially directed auditory warnings are better. When looking into glance transitions, it was found that subjects perform a visual search for the object. The auditory spatial cue is not applied to the object position and hence, shows no potential to shift the attention towards objects compared to undirected auditory warnings. This result seems contrary to what literature implies (e.g. high spatial resolution capability (in Goldstein, 2007); faster reaction towards spatial stimuli (Ho et al., 2006; Lampar, 2011)). Those statements are the results of studies, when the subjects are “active” listeners. In the present studies, hearing and processing auditory stimuli was part of the (very simple) driving task, the processing of the visual secondary task, object perception with the help of a warning and finally a response selection and execution (compare Wickens & Hollands, 2000). Hearing is a much more passive activity during the present studies and therefore, the mentioned benefits seem to lose their effectiveness.

The third study combined best results of both studies (visual directed and auditory undirected) depicts a multimodal spatial warning system. Multimodal warnings with visual directed warnings are highly effective. Reaction times benefit from this warning design across all sectors. In comparison with recent literature the relative reaction time reduction for multimodal warnings compared to uni-modal warnings was similar. Biondi et al. (2017) found even lower reaction times but only for brake reactions and not a visual search task as the present studies demanded. The higher effectiveness by using two redundant warning modalities was also proven by Lees at al. (2012). One limitation mentioned was that in a multimodal setup a visual cue is able to affect the advantages of solely auditory warnings (see Fernandez-Duque & Posner, 1996). For the present studies the visual cue benefits towards the searching task. When looking at the gaze data, it was found, that the auditory signal is shifting the attention back to the road and the directed visual warnings are shifting the attention towards the objects. This has a great meaning for the driving task because the warning design supports the driver at choosing and interpreting important information in his traffic and environmental situations. The chance of misinterpretation of traffic situations could be reduced significantly, especially in case of time constrains, high complexity or missing of relevant information.

One limiting factor for the present studies is, that the test persons are distracted by a secondary task. They were cognitively distracted and constantly aware of a required reaction which typically does not happen under actual conditions. Since the attraction is already known and expected, the accuracy of identification is reduced. It is assumed that an appropriate reaction might take longer under real conditions.
Conclusion

In conclusion it can be said that the demonstrated LED-HUD in its form has a high effectiveness regarding the reduction of reaction times. Directed warnings are beneficial with respect to large distances but disadvantageous regarding warning positions out of sight. While spatially directed auditory signals seem not to be fully capable to counteract this, it was found that they at least provide a better attention shift back to the road than on a particular object positioned in space. The multimodal study proved that the combination of warning design helped to shorten reaction times. This warning design counterbalances the advantages and disadvantages of both the visual and auditory warning designs.

Typical situations where spatially directed warnings can save time and hence, make driving safer and more comfortable are as following: complex situations (within the city or at crossing points), restricted environmental conditions (reduced visibility, darkness) or if the driver is distracted and has to interpret current automotive and traffic situations very fast. An important future application can be autonomous driving when the driver is getting a take-over request from the vehicle. In such situations, the driver needs to be fully aware of the situation around him. A multimodal directed warning implemented in an ADAS supports the driver to regain situational awareness as spatially directed warnings have the potential to enable a faster orientation which is needed to recognize relevant objects and to react on them properly.

For further research advanced technical approaches are possible. An optimised presentation of a directed warning can be realised as an animation of the optical cue could guide the attention toward relevant objects. Another opportunity could be the adaption of the LED-HUD warning to the position of the head. But this requires further technical installations, e.g. a Head-Tracker. Further research is also required regarding the adaption of warning designs and timings to the drivers’ (emotional) condition.

References


