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Cooperative warning systems: The impact of false and unnecessary alarms on drivers' compliance

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ABSTRACT

Cooperative warning systems have a great potential to prevent traffic accidents. However, because of their predictive nature, they might also go along with an increased frequency of incorrect alarms that could limit their effectiveness. To better understand the consequences associated with incorrect alarms, a driving simulator study with $N = 80$ drivers was conducted to investigate how situational context and warning urgency jointly influence drivers' compliance with an unreliable advisory warning system (AWS). The participants encountered several critical urban driving situations and were either assisted by a 100% reliable AWS, a 60% reliable AWS that generated false alarms (without obvious reason) or a 60% reliable AWS that generated unnecessary alarms (with plausible reason). A baseline drive without any assistance was also introduced to the study. The warnings were presented either only visually or visual-auditory. In line with previous research, drivers' compliance and effectiveness of the AWS was reduced by false alarms but not by unnecessary alarms. However, this so-called *cry wolf effect* (Breznitz, 1984) was only found in the visual-auditory condition, whereas there was no effect of warning reliability in the condition with visual AWS. Furthermore, false but not unnecessary alarms caused the participants to rate the AWS less favourably during a follow-up interview. In spite of these negative effects of false alarms, a reduction in the frequency of safety-critical events (SCEs) and an earlier braking onset were evident in all assisted drives compared with that of non-assisted driving, even when the AWS was unreliable. The results may thus lower concerns about the negative consequences of warning drivers unnecessarily about upcoming traffic conflicts if the reasons of these alarms are comprehensible. From a perspective of designing AWS, we recommend to use less urgent warnings to prevent the *cry wolf effect*.

1. Introduction

1.1. Background and scope of the study

In Germany, most accidents with personal injury are reported in urban areas with most of them happening in complex driving situations, such as intersections (Federal Statistical Office, 2013). Consequently, assisting drivers in these situations has a great potential to improve traffic safety. However, driver assistance that is merely based on on-board perception of the vehicle environment, such as a camera or radar, may not be capable of sufficiently analysing the driving environment in these conflict situations to provide comprehensive driver support (Seeliger et al., 2014). Specifically, the recognition and tracking of vulnerable road users and that of partly or even fully occluded road users is necessary to assist the driver efficiently (Edquist et al., 2012; Hamdar et al., 2016; Marciano and Yeshurun, 2015; Naujoks et al., 2015a,b; Rogé et al., 2012).

Driver assistance based on cooperative perception (e.g., car-to-car or car-to-infrastructure communication) has received considerable interest because it may provide a solution to these technical limitations by fusing vehicle localised environmental perception with information provided by other road users or the infrastructure (e.g., sensors mounted to traffic lights at intersections). Several national (e.g., sim^{TD} and Ko-FAS) and European research projects (e.g., INTERSAFE and DRIVE C2X) have thus dealt with the technological advancement of *cooperative perception*. Similar technological developments, like research on so-called *connected vehicles*, take place on an international level. For example, the US Department of Transportation currently runs a Connected

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Vehicle Deployment Program on three deployment sites (USDOT, 2015).

A promising application of cooperative perception is to inform drivers about impending conflict situations, even if the conflicting road user is occluded from the host vehicle's point of view (i.e., *advisory warnings*, see Seeliger et al., 2014; Naujoks et al., 2015a,b; Maag et al., 2015). The potential of these predictive warning systems to enhance driving safety has been shown repeatedly in different contexts, such as congestion tail warnings (Totzke et al., 2012; Werneke et al., 2013; Winkler et al., 2016), obstacle warnings (Mahr et al., 2010) and intersection collision warnings (Lenné et al., 2008; Naujoks and Neukum, 2014a; Zarife, 2014).

So far, these studies have dealt with perfectly reliable warning systems. However, assisting the driver by means of cooperative perception technology requires the modelling and prediction of the traffic situation based on fused sensor data. Due to the probabilistic nature of this cooperative perception approach, cooperative warning systems will not be perfectly reliable, which might in turn decrease the warnings' usefulness. In a literature review, Wickens and Dixon (2007) concluded that warning systems that are less than 70% reliable (with a confidence limit of roughly 14%), were not beneficial for human operators.

Reliability of warning systems can influence driver behaviour in several ways. Previous research has repeatedly revealed that false alarms reduce compliance with warning systems, for example by increasing reaction times, a phenomenon that has been labelled the *cry wolf effect* (Breznitz, 1984; Getty et al., 1995; Sorkin, 1988). The *cry wolf effect* has been named after the fable by Aesop about the "The boy who cried wolf"; however, in human factors psychology, it is not a young shepherd boy that has warned of a wolf worrying the sheep too often but an automated warning system that has issued too many false alarms (Roulston and Smith, 2004). The reason for a decreased compliance caused by false alarms may be a diminished contingency between the presentation of a stimulus, i.e., the driver warning, and the need for a reaction (Kiesel and Miller, 2007). The *cry wolf effect* is well-known from other applied research settings, such as aviation (Pritchett, 2001), medicine (Kestin et al., 1988; Meredith and Edworthy, 1995) or process management (Kragt and Bonten, 1983; Lee and Moray, 1992). In the worst case, users ignore or even switch off warning systems because the rate of false alarms is too high. In contrast to false alarms, missed alarms represent situations in which a traffic conflict that the driver should attend to does not trigger a warning signal. Missed alarms can lead to increased reaction times to critical situations as well as an increased crash risk compared with non-assisted driving (Mahr et al., 2010; Yamada and Kuchar, 2006).

The present paper revisits the issue of how false alarms influence cooperative warning effectiveness. By means of cooperative perception, drivers are assisted by an *advisory warning system* (AWS) in situations in which the conflicting road users are occluded when the driver approaches (e.g., by parked cars on the side of the road); this situation can only be resolved by cooperative warning systems. However, precisely in these situations, the reliability of the warning system might largely influence drivers' compliance because drivers cannot directly verify the correctness of the alarm. Within this context, two research questions are investigated that have not been comprehensively dealt with by prior research, namely, the presence of situational indicators from which the driver can infer the reason why a false alarm has occurred and the impact of the warning urgency.

1.2. False alarms effects on warning effectiveness

To date, most studies dealing with the *cry wolf effect* in the context of driver warning systems have focused on situations in which false alarms are presented without any reason (e.g., Bliss and Acton, 2003; Cummings et al., 2007; Yamada and Kuchar, 2006). These types of alarms may be most likely due to technical failures of the warning system. Alternatively, it is also possible that an alarm is issued because the warning system detected a potential conflict situation; however, as the situation develops further, the conflict resolves such that there is no imminent accident risk from the driver's point of view. These types of unnecessary alarms, thus, represent failures of the situational analysis and prediction involved in the generation of the warning (Weidl and Breuel, 2012; Weidl et al., 2013). For example, a pedestrian that is standing on the side of the road and is about to cross into the road may trigger an alarm, but the pedestrian may finally not enter the road as the host vehicle approaches. Consequently, the driver may not have to react to the warning at all.

According to Lees and Lee (2007), unnecessary alarms differ from "truly" false alarms because they provide the opportunity to understand the *process* of the warning system (cf. Lee and See, 2004). Understanding the *process* involved in the generation of the warning may increase trust in the warning system (Lee and See, 2004) and may consequently prevent diminished compliance despite unnecessary alarms (Lees and Lee, 2007). The distinction between false alarms and unnecessary alarms is illustrated in Table 1.

One may assume that the *cry wolf effect* would not occur in situations with unnecessary alarms because the driver is able to understand the situational determinants of unnecessary alarms (cf. Dzindolet et al., 2003). For example, in a study by Cotté et al. (2001), alarms of a collision warning system warned drivers of obstacles during a simulated drive. Thereby, false alarms occurred either without any obvious reason or unnecessary alarms occurred in situations in which objects on the side of the road could have caused the alarms. False and unnecessary alarms both decreased compliance with the warning system. These results contradict the results of Lees and Lee (2007) who reported that only false alarms, not unnecessary alarms, had a detrimental effect on drivers' compliance. These mixed empirical results beg the question whether false and unnecessary alarms cause different consequences on drivers' compliance and subjective evaluation of the warning system, which will be revisited in this study. In addition, we explore the impact of warning urgency on false and unnecessary alarms because we hypothesize that more urgent but false alarms are more detrimental for drivers' compliance.

1.3. Urgency and false alarm effects

From the driver's point of view, using more than one modality in the alarm design delivers a higher level of subjective urgency (Politis et al., 2013). Accordingly, *imminent collision warnings* in automobiles are usually presented in more than one modality to decrease reaction times and to enhance alarm effectiveness (ISO 15623:2013). Multimodal presentation of warning signals can speed up the cognitive processes involved in the selection and execution of an appropriate response, such as braking or steering. The advantageous effect of presenting more than one stimulus at once that requires a reaction, so-called *redundancy gain*, has been demonstrated repeatedly in cognitive psychology research (cf., Miller, 1982; Raab, 1962). Another goal of multimodal warning systems is to draw the driver's attention to a visual display on which relevant information is presented if the driver's gaze is not oriented towards that direction (Campbell et al., 2007). Consequently, the advantage of a multimodal warning system in the context of *imminent collision warnings* has been demonstrated in various studies (e.g., Ho et al., 2007; Kramer et al., 2007).

Nevertheless, warning urgency may be an important design aspect of cooperative warning systems. The previously mentioned studies mainly focussed on *imminent collision warnings* (Lenné and