

Designing Auditory Warning Signals to Improve the Safety of Commercial Vehicles



Johan Fagerlönn

Designing auditory warning signals to improve the safety of commercial vehicles

Johan Fagerlönn

Luleå University of Technology

Division of Human Work Science

Department of Business Administration, Technology and Social Sciences

Engineering psychology

2011

Cover picture: Artwork by Nigel Papworth

Printed by Universitetstryckeriet, Luleå 2011

ISSN: 1402-1544
ISBN 978-91-7439-336-1

Luleå 2011

www.ltu.se

ABSTRACT

Based on four studies, this thesis aims to explore how to design auditory warning signals that can facilitate safer driving by operators of heavy goods vehicles. The first three studies focus on the relationships between certain characteristics of auditory warnings and various indicators of traffic safety. A deeper understanding of these relationships would allow system developers to design auditory signals that are better optimised for safety. The fourth study examines the opinions of both vehicle developers and professional drivers regarding warning attributes.

One major conclusion is that meaningful warning sounds that are related to the critical event can improve safety. As compared with arbitrarily mapped sounds, meaningful sounds are easier to learn, can improve drivers' situation awareness, and generate less interference and less annoyance. The present thesis also supports the view that commercial drivers' initial acceptance of these sounds may be very high.

Annoyance is an especially important aspect of warning design to consider; it can negatively influence driving performance and may lead drivers to turn off their warning systems. This research supports the notion that drivers do not consider that negative experience is an appropriate attribute of auditory warnings designed to increase their situation awareness. Also, commercial drivers seem to report, significantly more than vehicle developers, that having less-annoying auditory warnings is important in high-urgency driving situations. Furthermore, the studies presented in this thesis indicate that annoyance cannot be predicted based on the physical properties of the warning alone. Learned meaning, appropriateness of the mapping between a warning and a critical event, and individual differences between drivers may also significantly influence levels of annoyance.

Arousal has been identified as an important component of driver reactions to auditory warnings. However, high levels of arousal can lead to a narrowing of attention, which would be suboptimal for critical situations during which drivers need to focus on several ongoing traffic events. The present work supports the notion that high-urgency warnings can influence commercial drivers' responses to unexpected peripheral events (i.e., those that are unrelated to the warning) in terms of response force, but not necessarily in terms of response time.

The types of auditory warnings that will be developed for future vehicles depend not only on advances in research, but also on the opinions of developers and drivers. The present research shows that both vehicle developers and drivers are aware of several of the potentially important characteristics of auditory warnings. For example, they both recognise that warnings should be easy to understand. However, they do disagree regarding certain attributes of warnings, and, furthermore, developers may tend to employ a "better safe than sorry" strategy (by neglecting factors concerning annoyance and the elicitation of severe startled responses) when designing high-urgency warnings.

Developers' recognition of the potentially important attributes of auditory warnings should positively influence the future development of in-vehicle systems. However, considering the current state of research regarding in-vehicle warnings, it remains challenging to predict the most suitable sounds for specific warning functions. One recommendation is to develop a design process that examines the appropriateness of in-vehicle auditory warnings. This thesis suggests an initial version of such a process, which in this case was produced in collaboration with system designers working in the automotive industry.

To Lena

APPENDED PAPERS

Paper 1

Fagerlönn, J., & Alm, H. (2010). Auditory signs to support traffic awareness. *IET Intelligent Transport Systems*, 4(4), 262-269.

Paper 2

Fagerlönn, J. (in press). Urgent alarms in trucks: effects on annoyance and subsequent driving performance. *IET Intelligent Transport Systems*.

Paper 3

Fagerlönn, J. (2011). Making auditory warning signals informative: examining the acceptance of auditory icons as warning signals in trucks. In *Proceedings of the 6th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 95-101). Iowa City: University of Iowa.

Paper 4

Fagerlönn, J. The design of auditory warning signals: what are the opinions of vehicle developers and truck drivers? In preparation to be submitted to a scientific journal or conference.

ACKNOWLEDGEMENTS

Many people and several organisations have contributed in one way or another to the work presented in this thesis.

First of all, I would like to express my gratitude to my academic supervisor at the Luleå University of Technology, Håkan Alm. Thank you for your quick and constructive input on manuscript drafts, and for the hours spent in inspiring discussions with me, which, for some reason, felt like minutes rather than hours.

My deepest gratitude goes to Katarina Delsing at the Interactive Institute – Sonic Studio. Thank you for your invaluable work in initiating and maintaining this research project.

Thanks also to Robert Friberg at Scania CV AB, my industrial supervisor throughout this project. Not only did he help with the project itself, but he also engaged me in off-duty activities, such as challenging pub quizzes.

Thanks to Torkel Varg at Scania CV AB for supporting the project from its start, and thanks to Hanna Johansson, who was the project manager for a significant part of the project. Also, thanks to Anna Sirkka for her help with the planning of studies and her great feedback on ideas and written texts.

Thanks to Mats Liljedahl, Stefan Lindberg, Nigel Papworth, Sofia Larsson, Ola Lidström and the rest of the “Sonic crew” for providing an inspiring and friendly working environment at the Interactive Institute in Piteå. Special thanks go to Stefan for his work in designing the sounds used in the studies throughout the project.

I would also like to express my gratitude to the personnel at the Swedish Road and Transport Research Institute in Linköping. Thanks for your hospitality and teamwork during the planning and realisation of the challenging experiment. Special thanks to Anders Andersson, both for his excellent, on-demand problem-solving abilities and his personal engagement in the project.

I would also like to thank all the participants in the various research studies. Special thanks go to the personnel at the haulage firm Scania Transportlaboratorium AB in Södertälje.

My eternal gratitude goes to my supportive and understanding family, Lena, Robin, and Sam (who was born during this project), and my dear mother and father. I would like to dedicate a special thought to my father, who unfortunately left us in April 2011. Rest in peace, Dad...

And last but not least, this work was made possible through the financial support of Scania CV AB, the Swedish Governmental Agency for Innovation Systems (Vinnova), Swedish ICT, and the competence centre Virtual Prototyping and Assessment by Simulation (ViP).

TABLE OF CONTENTS

1	BACKGROUND FOR THE RESEARCH	1
1.1	WHAT IS A WARNING?	1
1.2	THE INFLUENCE OF WARNINGS ON SAFETY	1
1.2.1	Effectiveness	1
1.2.2	Costs	2
1.3	EFFICIENCY AND COSTS OF AUDITORY WARNINGS	2
1.4	OBJECTIVES AND SCOPE	2
2	DRIVING	4
2.1	RASMUSSEN'S FRAMEWORK	4
2.2	DRIVING IN A SAFETY-CRITICAL SITUATION	4
2.3	ATTENTION AS A LIMITED-CAPACITY RESOURCE	5
3	TIME-SHARING AND PERFORMANCE	6
3.1	THE MULTIPLE RESOURCE MODEL	6
3.2	INATTENTIONAL BLINDNESS	7
3.3	EVIDENCE OF AUDITORY TASK INTERFERENCE IN DRIVING	7
3.3.1	Effects on different subtasks of driving	7
3.3.2	Effects of task difficulty	8
3.3.3	Effects of only listening	8
3.4	CONCLUSIONS REGARDING TIME-SHARING	8
4	AROUSAL AND PERFORMANCE	9
4.1	THE OPTIMAL AROUSAL LEVEL	9
4.2	THE EFFECTS OF AROUSAL ON INFORMATION PROCESSING	10
4.3	CONCLUSIONS REGARDING AROUSAL	11
5	ANNOYANCE OF WARNINGS	12
5.1	THE DRAWBACKS OF ANNOYANCE	12
5.2	ANNOYANCE AND WARNING DESIGN	12
5.3	CONCLUSIONS REGARDING ANNOYANCE	13
6	DRIVER DISTRACTION	14
7	NON-VERBAL SOUNDS AS CARRIERS OF URGENT INFORMATION	15
7.1	PERCEIVED URGENCY	15
7.2	EARCONS AND AUDITORY ICONS	15
7.2.1	Auditory icons and earcons as warnings	16
7.3	NATURAL WARNING SOUNDS	16
8	SITUATION AWARENESS	18
8.1	CONCLUSIONS REGARDING SITUATION AWARENESS	18
9	SUMMARY OF STUDIES	19
9.1	STUDY 1	19
9.2	STUDY 2	21
9.3	STUDY 3	23
9.4	STUDY 4	25
10	CONCLUSIONS AND IMPLICATIONS	27
11	TWO NEW DESIGN TOOLS	29
12	REFERENCES	30
	APPENDIX: THE NEW DESIGN TOOLS	37

1 Background for the research

The aim of the research presented in this thesis has been to gain better insight into how to design auditory warning signals that will facilitate safer driving in heavy goods vehicles. Drivers may have several goals, such as minimising travel time or travel costs. However, the present research focuses on how to develop technology that helps drivers to reach one particular goal: that of avoiding traffic accidents. Heavy goods vehicles are currently involved in a disproportionate number of serious traffic incidents (Strandroth, 2009; Björnstig, Björnstig & Eriksson, 2008; National Highway Traffic Safety Administration, 2008). Every year, approximately one hundred people are killed in accidents involving heavy goods vehicles in Sweden. This figure represents approximately 20 percent of all deaths from road accidents. Both the degree of injury and degree of disability caused by these accidents suggest that collisions with vehicles of this type produce more serious consequences than do other collisions (Strandroth, 2009). The National Highway Traffic Safety Administration (NHTSA, 2008) reports that in 2007, large trucks travelled 7 percent of the total vehicle miles driven, whereas they accounted for 11 percent of all traffic fatalities.

In recent years, the number of in-vehicle functions available to drivers has increased rapidly. The implementation of Intelligent Transport Systems (ITSs) is associated with increased traffic safety. ITSs commonly include warning signals used to alert drivers. The combination of new technology and auditory warnings could help drivers to make appropriate decisions and act appropriately in dangerous situations. However, the increasing number of ITSs also makes it increasingly important to determine how warnings can best be designed to maximise their potentially positive effects on driving safety while minimising their negative effects.

1.1 What is a warning?

An in-vehicle warning can take many different forms. For example, it can be communicated to a driver using different sensory modalities or combinations of modalities. According to Edworthy and Adams (1996), warnings are artefacts that have been designed to represent the danger to which they refer. Accordingly, warnings occur separately from the dangerous situation itself. For example, a driver perceives various informational cues within the traffic environment in a dangerous situation (e.g., when an approaching vehicle crosses the centre line). However, such cues do not constitute a warning. Rather, a warning occurs only when a designed artefact (e.g., a flashing light, a written message or a sound) is triggered by an ITS.

Wickens and Hollands (1999) state that the goal of a warning is to get the user to comply with it, and thereby employ the product in a safe way or avoid unsafe behaviour in a threatening situation. However, it is important to realise that drivers will make use of both the warning and other cues, including internal cues based on previous experience, when making decisions about how to act.

1.2 The influence of warnings on safety

1.2.1 Effectiveness

A warning improves traffic safety when it helps the driver to avoid or eliminate the hazard. If one warning is more helpful in this regard than another, it is more effective. The effectiveness of particular warnings may depend on the speed and accuracy of the driver's response. To what extent speed is important depends heavily on the urgency of the situation. In a high-urgency situation (e.g., a near-collision), the driver has little time to respond, and thus, seemingly "small" improvements in response time can greatly increase safety.

1.2.2 Costs

When the driver perceives a warning, he or she is already engaged in safety-critical activities. Therefore, to evaluate the effect of a warning on safety, one must consider whether it negatively influences the driver's ability to perceive, process or respond to other safety-critical information. Furthermore, if the design of the warning for some reason causes the driver to turn off the whole system or the system sound, the potential safety benefits will decrease or disappear.

1.3 Efficiency and costs of auditory warnings

Using sound to warn the driver may be preferable to using other sensory modalities; indeed, sound can be a more efficient and safer form of warning. Auditory cues can be perceived from any direction and are independent of the driver's visual focus. Thus, it is more likely that an auditory warning will be detected, which is of course necessary for it to be effective. In addition, retrieving information from sounds does not require the driver to shift his or her gaze away from the road. Because driving is a highly visual task, maintaining visual focus is critical. In fact, it has been estimated that as much as 90 to 95 percent of information used while driving is visual (e.g., Booher, 1978). The importance of sufficient visual perception during driving was illustrated in the "100-car study" (Dingus et al., 2006). The study showed that visual inattention was a factor in 78% of crashes and 65% of near-crashes. Glances away from the roadway for more than 2 seconds may be especially dangerous (Klauer et al., 2006).

However, as will be described later in this thesis, auditory information can also have negative effects on the ability of drivers to perceive and process visual information. Furthermore, it is well known that auditory warnings can be annoying.

1.4 Objectives and scope

One objective of this thesis has been to examine the relationships between characteristics of auditory warnings in commercial vehicles and indicators of traffic safety. If research can identify these relationships, and determine why they exist, system developers will be better prepared to design auditory signals that improve traffic safety. Developers will be able to more accurately predict which sounds function best as warnings and to anticipate negative effects of those sounds on safety.

This thesis focuses on drivers of a particular type: professional truck drivers working in Sweden. This thesis also focuses on auditory warnings used in systems designed to inform drivers about dangers in the traffic environment. Furthermore, the research conducted focuses on the effectiveness and negative effects of auditory warnings rather than entire warning systems. For example, automating aspects of the driving, high frequencies of false warnings, and inappropriate warning timing can all negatively impact safety. However, these effects are not covered in this thesis.

The three first studies presented in this thesis focus on the relationships between characteristics of auditory warnings and (1) learnability, (2) traffic situation awareness, (3) cognitive effort, (4) annoyance, (5) attentional narrowing, and (6) initial acceptance. The specific aims of each study are described below.

Study 1. This study examines the learnability of different sound types, their potential to increase situation awareness, the cognitive effort required to process them, and the annoyance they may cause. Warnings that sound like the traffic object they represent (auditory icons) are compared to verbal sounds (keywords) and to musical sounds (abstract earcons) that are arbitrarily mapped to

traffic objects. One specific aim was to examine the relative effects of sounds on cognitive effort after the driver had a chance to learn the warnings.

Study 2. This study investigates how the psychoacoustic parameters of warnings affect perceived annoyance and attentional narrowing (i.e., to what degree they decrease the ability of drivers to perceive and respond to information that is not related to the warning).

Study 3. This study investigates the initial acceptance of auditory icons as warning signals among commercial drivers.

Which types of auditory warnings will be used in future vehicles also depends on which attributes of auditory warnings are important to vehicle developers and drivers (e.g., the level of annoyance caused or whether the urgency level is appropriate). The second aim of the present research has been to examine both developers' and drivers' opinions about the importance of a range of warning attributes that past research has indicated to be important.

Study 4. In this study a questionnaire was used to examine the opinions of vehicle developers and commercial drivers regarding properties of warnings that have been identified as potentially important in previous research. The motive of the examination was to identify helpful aspects of the developers' and drivers' opinions, using them to maximise the success of warning design and avoid some of its pitfalls.

2 Driving

For many people, driving a vehicle is an every-day activity. Still, it is a complex activity that is difficult to describe as a whole. Some authors have described driving not as a single task but instead as a combination or hierarchy of tasks. Rumar (1990), for example, suggests that driving consists of eight main types of tasks, including strategic tasks (e.g., choices regarding transport mode and decisions about destinations and routes) and traffic-related tasks (those that involve interactions with other road users). Michon (1985) describes driving as a problem-solving task that can be separated into three levels of skills and control: strategic (trip planning), tactical (manoeuvring) and operational (vehicle control). Hollnagel (2002) applies the “Extended Control Model” (ECOM) to driving, which suggests that the driving task involves the pursuit of several simultaneous sub-goals with different timeframes. These goals are associated with four simultaneous, interrelated control layers: tracking, regulating, monitoring and targeting control.

2.1 Rasmussen’s framework

One common approach to the categorisation of tasks performed by users is the framework of “skill-, rule- and knowledge-based performance” presented by Rasmussen (1983). According to the framework, skill-based performance characteristically takes place without conscious attention or control, yielding smooth, automated patterns of behaviour. In rule-based performance, the person acts based on previously learned rules. For example, rules can be formulated from previous successful encounters with a similar situation. Knowledge-based behaviour takes place in unfamiliar situations for which no specific rules have been formulated (Rasmussen, 1983). The three levels of performance are associated with different levels of automaticity, and skill-based behaviour is the most automated. More automatic behaviour is more rapid and accurate and requires fewer mental resources. The level of automaticity depends on the amount of training the person has undergone and the difficulty of the task (Wickens et al., 1999).

Hale, Stoop and Hommels (1990) propose that Rasmussen’s performance levels can be mapped onto the levels of driver skill and control suggested by Michon (1985). Combining these two frameworks illustrates that the subtasks of driving can become more automated and less effortful after driver training. For instance, fundamental driving tasks such as steering and braking, can be demanding for a novice driver, whereas experienced drivers perform them at a highly automated level.

2.2 Driving in a safety-critical situation

The present thesis focuses on what occurs when experienced drivers encounter a safety-critical situation. Even though experienced drivers may perform many driving-related tasks with less effort compared to inexperienced drivers (Patten et al., 2006), safety-critical situations are still likely to be demanding for them. Safety-critical situations are likely to be infrequent and to occur unexpectedly. As Ranney (1994) states, novel and unexpected driving situations can impede skill-based performance and require knowledge-based (more demanding) processing. Furthermore, in safety-critical situations, the driver will have to search the environment for information that is relevant to the threatening situation. It has been suggested that hazard detection is an effortful activity, even for experienced drivers (McKenna & Farrand, 1999). Moreover, if a safety-critical situation is complex – for example, because it involves several road users – the driver will have to divide his or her attention among several ongoing and developing events on the road.

When (or immediately after) the auditory warning of a road event is triggered, the driver will likely experience a great amount of cognitive effort and stress. In these situations, auditory warnings need

to support rapid, appropriate decision-making, helping drivers decide how to respond to the danger while simultaneously creating the smallest possible negative effect on the driver's ability to cope with the whole driving situation.

2.3 Attention as a limited-capacity resource

One established model that can be used to analyse task performance is the human information processing system (HIPS) model presented by Wickens et al. (1999), see figure 1. The model suggests that information processing is performed in a series of stages through a feedback loop with the environment. In the model, attention is conceptualised as a supply of mental resources. These resources are necessary during the various stages of information processing, from the information selection phase to the response execution processes.

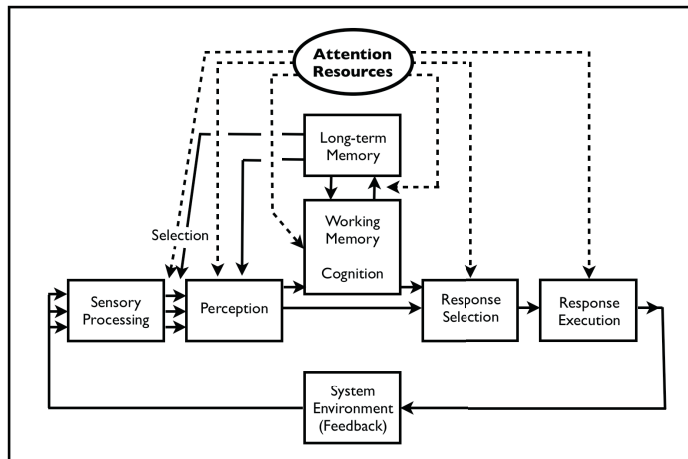


Figure 1 *The Human Information Processing System presented by Wickens et al. (1999).*

Salient cues are believed to trigger involuntary orienting responses that are accompanied by the redirection of attention (Cowan, 1995; Kahneman, 1973; Shelton et al., 2009; Solokov, 1963). Thus, auditory warnings will likely demand mental resources from the driver. It is of crucial importance that the warning attracts attention if it is to be effective. However, to what extent an informing auditory warning will require mental resources depends heavily on the cognitive operations needed to interpret the sound. Sounds that require the driver to perform conscious cognitive operations such as reasoning and rehearsal can slow information processing and significantly increase the level of mental resources required.

One common belief is that mental resources are limited (Cowan, 1995; Wickens et al., 1999; Norman et al., 1975; Kahneman, 1973). When resource demands exceed resource availability, the performance will worsen.

In some cases, performance will not improve even if more resources are invested in the task. Consider, for example, a person who is trying to interpret a message presented in an unfamiliar language. A driver who is attempting to understand an unfamiliar warning is similar. No matter what resources the driver invests in trying to process the sound, he or she will not be able to determine its meaning. Performance that is not limited by mental resources has been referred to as data limited (Norman & Bobrow, 1975).

3 Time-sharing and performance

Wickens et al. (1999) explain time-sharing as the division of attention among tasks. Perfect time-sharing occurs when tasks are performed concurrently as well as they would each be performed alone. When the level at which one of the tasks is performed decreases, dual-task interference has occurred.

One type of time-sharing occurs when a driver processes a warning simultaneously scanning the road. If performing the two tasks together has a negative effect on the level at which either task is performed, dual-task interference has occurred.

Wickens et al. (1999) emphasise the contribution of various factors to the level of dual-task interference. One factor is the total amount of resources required to perform the tasks in question. Another factor is the degree of similarity between the types of resources required to perform the particular tasks. Simultaneously performing two tasks that require the same processing resources (according to the structure of resources in the Multiple Resource Model (Wickens, 1980, 2002) is more likely to create interference.

3.1 The multiple resource model

Wickens (e.g., Wickens, 1980, 2002) designed a popular model for the use of multiple resources in human information processing. In the model, the resources that are available for information processing are distributed according to a structure that includes stages, modalities and codes (see figure 2). The three dimensions are described as somewhat independent of one another. For example, the resources used for the perception and cognitive processes are the same, but they are different from the resources used for response selection and execution.

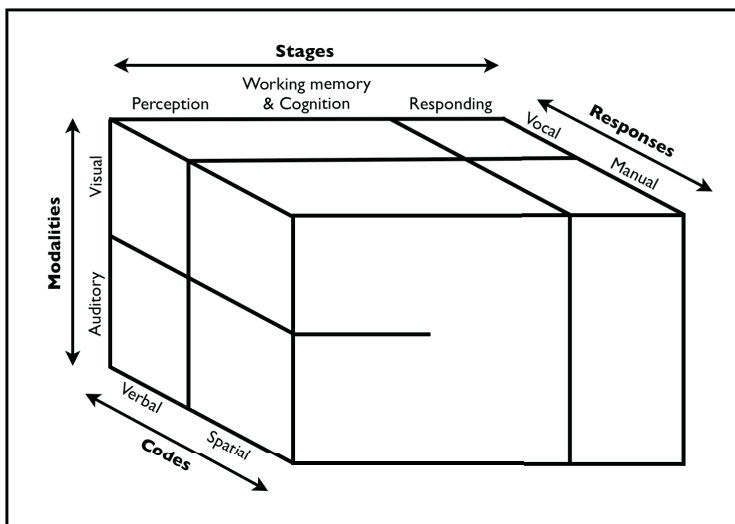


Figure 2 The Multiple Resources Model presented by Wickens et al. (1999).

The model indicates that cross-modal time-sharing (i.e., auditory-visual sharing) is preferable to intra-modal time-sharing (e.g., visual-visual sharing). However, the level of interference depends on the number of shared dimensions and the resource demand associated with the processes included in those dimensions. For example, presenting information to a driver using sound instead of a visual

display can be beneficial because it will require cross-modal rather than intra-modal time-sharing. However, if processing the auditory information requires more perceptual and cognitive resources, the benefits of utilising the auditory sense may be negated.

It should be noted there are other potential benefits of simultaneously using visual and auditory sensory channels besides those indicated by the Multiple Resources Model. Two visual tasks will likely require visual scanning between them, which can have a negative impact on performance (Wickens et al., 1999).

3.2 *Inattentional blindness*

Some researchers have questioned the appropriateness of using the theory of multiple resources to predict the level of interference caused by performing auditory tasks while driving. Strayer (2007), for example, favours the concept of “inattentional blindness” (Mack & Rock, 1998) as a way to explain the negative effects. Inattentional blindness occurs when a person looks at an object but does not consciously perceive it because he or she is not directing attention towards it (Mack et al., 1998). The inattentional blindness phenomenon can occur solely because the person does not expect or intend to perceive the object, but performing other attention-demanding tasks increases the probability that it will occur.

For instance, performing a more cognitively engaging auditory task will divert more of the driver’s attention from his or her driving, which will increase the risk of his or her missing unexpected visual information, even when the driver keeps his or her eyes on the road.

3.3 *Evidence of auditory task interference in driving*

Given the potential advantages of cross-modal information processing (as suggested in the Multiple Resources Model (Wickens, 2002)), one might ask whether an auditory task might have a negative effect on the predominantly visual task of driving.

A significant body of research has reported that auditory tasks can negatively impact driving performance and drivers’ ability to respond to visual information (e.g., Alm & Nilsson, 1995; Treffner & Barret, 2004; Patten et al., 2004; McKnight & McKnight, 1993). Many of these studies have focused on drivers’ use of mobile phones. However, it is still a matter of debate as to whether the interference of mobile-phone use actually results in an increased number of crashes. A number of recent studies have failed to report that mobile phone conversations significantly increase the risk of crash (Klauer et al., 2006; Olson et al., 2009; Young 2011).

3.3.1 *Effects on different subtasks of driving*

One interesting conclusion drawn from previous research is that auditory tasks seem to interfere particularly with hazard detection (response times to hazards) and judgement tasks (Horrey & Wickens, 2006; Brown, Tickner & Simmonds, 1969). Horrey et al. (2006) performed a meta-analysis of 23 studies that had examined the negative effects of mobile phone use. They concluded that the effects of mobile phone use on lane-keeping seem to be less significant than the effects on hazard detection and response. Furthermore, McKenna et al. (1999) reported that experienced drivers exhibit better hazard detection than novices. However, when the drivers performed auditory tasks while driving, the same level of hazard detection was exhibited by experienced and novice drivers.

3.3.2 Effects of task difficulty

Studies have also shown that increasing the level of difficulty of the auditory task or the driving situation can increase interference (Strayer & Johnston, 2001; Patten et al., 2004). For example, Patten et al. (2004) reports that drivers performing more difficult verbal tasks exhibited longer reaction times on a Peripheral Detection Task (PDT) than did those who were simply repeating numbers. However, some studies have failed to report statistically significant effects of increasing the difficulty of auditory tasks (McKnight et al., 1993).

3.3.3 Effects of only listening

A number of studies have reported no association between pure listening tasks and negative impact on visual change detection (Strayer et al., 2001; McCarley et al., 2004). However, inference has also been reported to derive from tasks that do not require subjects to respond verbally. Richard et al. (2002) reported that conducting an auditory version of the working memory span test (Baddeley et al. 1985) could affect a driver's ability to detect changes in traffic scenes. In addition, Pizzighello and Bressan (2008) reported that memorising auditory material and interpreting a story had negative effects on the detection of unexpected visual information.

3.4 Conclusions regarding time-sharing

Both theoretical models on human information processing, and empirical studies on interference of auditory tasks on driving, emphasise the need for auditory warnings that require little mental resources to be processed. Sounds that are designed to be informing, but require significant cognitive processing, will likely slow decision-making and responses. Furthermore, when a driver invests more mental resources in processing a warning, he or she will have fewer resources available for handling a demanding critical driving situation.

Also, if the driver has not learned how to interpret a warning, the information processing becomes data limited rather than resource limited. Such data limitations can undermine effectiveness, and if the driver invests significant effort in trying to understand the sound, significant interference may also result.

4 Arousal and performance

Arousal is activation of the autonomic nervous system (Juslin & Västfjäll, 2008). Arousal can also be described as a state of readiness to perform. It has been suggested that arousal and valence (or pleasantness) are two main underlying dimensions of affective descriptors (Bradley & Lang, 1994). The two dimensions form the “circumplex model of affect” presented by Russell (1980); see figure 3.

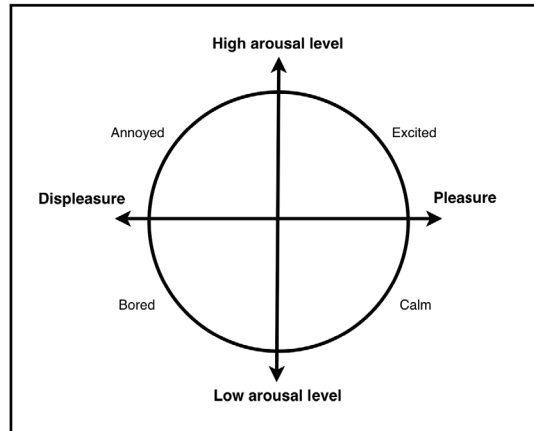


Figure 3 *Circumplex Model of Affect, adapted from Russel (1980).*

Arousal is a common reaction to stressors (Wickens et al., 1999) and can increase as a result of various changes in the environment, including increased cognitive demands and time pressure. Sounds that indicate a change in the environment will increase the activation of the central nervous system (Juslin et al., 2008). That is, sounds that meet certain criteria (e.g., fast, loud, and/or sudden sounds) will most likely increase arousal.

“Arousal potential” has been identified as an important characteristic of auditory warnings. The emotional reaction model presented by Västfjäll et al. (2006), see figure 4, suggests two main ways in which auditory warnings are processed and contribute to actions. If a sound has sufficient “arousal potential” (based on its acoustic properties), it will incite an immediate and rapid response. Conversely, if a sound does not have sufficient arousal potential, it will be compared with sound memories stored in the person’s long-term memory. If the sound is judged as novel or is associated with something dangerous, it will yield a response.

4.1 *The optimal arousal level*

The emotional reaction model presented by Västfjäll et al. (2006) implies that auditory warnings should have a certain degree of arousal potential, and should be familiar to the listener. But arousal levels should also be kept at a reasonable level to avoid inappropriate driver behaviour (Larsson et al., 2008). The concept of the “optimal arousal level” for task performance was introduced with the development of the Yerkes-Dodson model (Yerkes & Dodson, 1908). The model predicts a positive correlation between arousal levels and performance for very easy tasks. As tasks become more difficult, higher arousal increases performance to a certain point, but arousal levels that exceed that optimum will worsen performance.

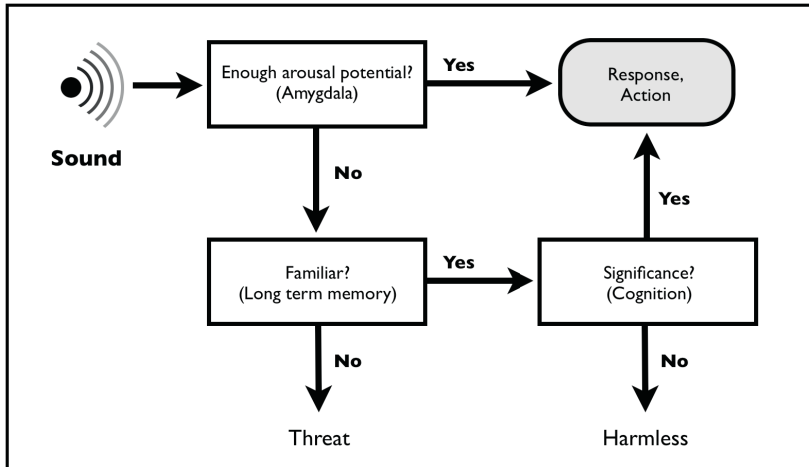


Figure 4 *The emotional reaction model presented by Västfjäll et al. (2006).*

4.2 *The effects of arousal on information processing*

It has been suggested that an arousing stimulus influences performance in various ways. For instance, the arousing stimulus may encourage enhanced perception of the stimulus (Anderson & Phelps, 2001) or enhanced long-term memory of the event (Cristianson et al. 1991). Easterbrook (1959) suggested that arousal will lead to a “narrowing of attention”; see figure 5. When a person is observing an emotional event, his or her attention will be focused primarily on the arousing details of the stimulus. As a result, the person will better encode those details but will not encode less relevant details as well.

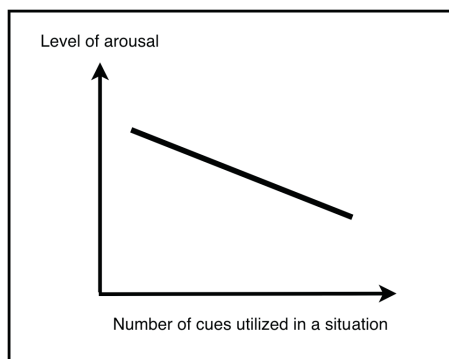


Figure 5 *Cue-utilisation hypothesis (Easterbrook, 1959).*

In accordance with the principle of “attentional narrowing”, researchers have reported that people are considerably less able to respond to peripheral stimuli when they are under stress, whereas their capacity to perform central tasks or tasks of primary importance is unaffected (e.g., Weltman, Smith & Egstrom, 1971). In the domain of driving, Chapman and Underwood (1998) reported that drivers who watched dangerous traffic events exhibited eye movements that indicated a narrowing of the visual search.

4.3 Conclusions regarding arousal

In-vehicle warnings should probably cause some degree of arousal if they are to be effective. However, high arousal levels can have negative consequences. Attentional narrowing is one potential side effect that can be of crucial importance in driving situations that require the driver to simultaneously direct his or her attention to several events in the traffic environment.

5 Annoyance of warnings

Annoyance is an affective state and is one of the most studied effects of sound on humans. The annoyance created by an auditory warning might be more appropriately described as an emotional state than as a mood. According to Juslin et al. (2008), emotions are responses of relatively short duration (from a few minutes to a few hours) and intense affect that usually involve subjective feeling, physiological arousal, expression, action tendency, and regulation. In contrast, moods last longer (from several hours to multiple days) and are less intense than emotions. Furthermore, whereas emotions focus on a specific object, moods do not have a clear object.

In the previously described Circumplex Model of Affect (Russel, 1980) (see figure 3), annoyance would be positioned somewhere in the upper left quadrant (Remington, Fabrigar & Visser, 2000).

5.1 *The drawbacks of annoyance*

Annoyance is associated with negative experiences, which makes it an important effect to consider in system design, for at least four reasons.

First, according to emotion regulation theory (Gross, 2001), drivers may try to avoid experiencing negative emotions by avoiding the sound. Because salient sounds are generally hard to ignore, the only way for a driver to avoid an annoying sound may be for him or her to turn down the volume or turn off the entire system. Along these lines, it has been reported that in anaesthetic operating rooms, auditory warnings are often disabled because of their unpleasant sound characteristics (Block, Nuutinen & Ballast, 1999).

Second, emotional reactions make people focus on emotionally relevant objects. In the context of driving, this could mean that the driver would be led to focus on the dangerous situation after hearing the warning. However, if the system were causing severe annoyance, the driver might also focus on the negative aspects of the system rather than on his or her driving.

Third, it has been suggested that more negative emotions during driving are accompanied by more risky driving behaviours (Deffenbacher et al. 2001; King & Parker, 2008).

Forth, increased annoyance of auditory warnings has been found to contribute to increased driver workload (Wiese & Lee, 2004).

5.2 *Annoyance and warning design*

Research regarding sound annoyance has largely focused on environmental noise and various types of unwanted sounds. It has been suggested that annoyance may be predicted by physical and psychoacoustic measures such as loudness, sharpness, harmonic ratio, duration and tonality (Hiramatsu et al., 1978; Landström et al., 1995; Kahn, Johansson & Sundback, 1997). Annoyance may also be predicted by non-physical measures such as sound identity (Ellermeier, Zeitler & Fastl, 2004), predictability, controllability (Kjellberg et al., 1996), attitude towards the sound source (Taylor, 1984), and the extent to which the sound interferes with ongoing cognitive tasks (Zimmer, Ghani & Ellermeier, 2008). Furthermore, annoyance has been reported to be context- (Fucci et al., 1997) as well as somewhat subject-dependent (Berglund & Preis, 1997; Taylor, 1984).

For warnings presented in vehicles, a number of studies have investigated the relationships between warning characteristics and annoyance. It is rather well established that acoustic parameters that increase the perceived urgency of a warning signal also increase the sound's potential to become

annoying (Marshall, Lee & Austria, 2007; Wiese et al., 2004; Tan & Lerner, 1995). Some evidence also suggests that a driver experiences annoyance with a warning because he or she has learnt that the warning indicates a situation of a certain urgency level (McKeown, 2005; Marshall et al., 2007).

5.3 Conclusions regarding annoyance

It is not desirable for auditory warnings to cause annoyance. If two warnings are equally effective, but one of them is more annoying, the less annoying warning is likely more appropriate. However, because auditory warnings are designed to interrupt the driver and to express some degree of urgency, it is challenging to design effective warnings, especially high-urgency warnings, without the potential to become annoying. Negative cues (i.e., those that indicate a potential threat to our well being) may more efficiently (automatically) catch a person's attention compared with positive cues (Pratto & John, 1991). This factor may also make us respond faster in tasks that are relevant for the negative emotion (Estes & Verges, 2008). Along these lines, it has been reported that warnings that are more activating and negative result in faster response times while driving (Larsson et al., 2008).

However, it is of great interest to find ways to minimise annoyance. One such way may be to design auditory warnings based on acoustic properties that affect urgency more than they affect annoyance. Marshall et al. (2007) reported that pulse duration, interpulse interval, alert offset, alert duty cycle, and sound type may be particularly promising parameters for increasing urgency with relatively little effect on annoyance. Furthermore, developers may be able to reduce the potential for warning-related annoyance by avoiding the exaggeration of sound properties that are associated with annoyance. For example, developers can avoid extreme acoustic properties (e.g., very loud sounds) or sounds that could interfere unnecessarily with the driver's ongoing cognitive processes. To better understand how to minimise the annoyance of auditory warnings, we need to learn more about the factors that influence the perception of these sounds as annoying.

6 Driver distraction

The negative effects of in-vehicle technology on the attention and performance of drivers are sometimes referred to as driver distraction. Should the negative effects of in-vehicle warnings on the ability of drivers to drive safely be considered driver distraction?

The term “driver distraction” is commonly used in both academia and the industry. However, there is no universal definition for this term. Lee, Young and Reagan (2008) presented 14 different definitions culled from the previous literature, all with different specifications and scopes. Nine of these 14 definitions specify that in driver distraction, attention is “diverted”, “shifted”, “taken”, “withdrawn” or “redirected” from “driving”, “the driving task” or “stimuli that is critical for safe driving”.

Accordingly, it could be appropriate to say that a warning that diverts drivers’ attention from the driving task causes driving distraction. However, such a claim would require a definition of driving that excludes the processing of in-vehicle warnings. If interpreting in-vehicle warnings are considered to be part of driving, it seems inappropriate to say that warnings causes driver distraction.

It may be more appropriate to say that a warning is causing driver distraction if it impacts drivers attention in a way that is negative for driving safety, and which is not compensated by any positive effects on driving safety that the warning brings. For instance, a warning that makes the driver shift attention towards the wrong direction would likely be distracting rather than helpful.

7 Non-verbal sounds as carriers of urgent information

The studies in the present thesis focus primarily but not exclusively on the design of non-verbal sounds as carriers of urgent information. This chapter briefly introduces previous research in this area.

7.1 Perceived urgency

Perceived urgency is one of the most commonly investigated properties of auditory warnings. Urgency has been defined as “something that requires immediate action or attention” (Suied, Susini & McAdams, 2008). Matching the perceived urgency of a warning with the urgency of the dangerous situation has been called “urgency mapping” (Edworthy & Adams, 1996). It has been argued that appropriate urgency mapping can help users to prioritise information, enhance warning interpretation, and reduce both interference and workload (Wiese et al., 2004).

A significant body of research has established that the perceived urgency of warnings depends on acoustical properties such as frequency content and rhythm (Edworthy, Loxley & Dennis, 1991; Hellier, Edworthy & Dennis, 1993; Haas & Edworthy, 1996). Thus, an auditory warning can give the listener fundamental information about the situation, even when the listener does not know the exact meaning of the sound. However, when a person learns the meaning of a warning sound, the perceived urgency associated with the sound may be determined based on that meaning rather than on the sound’s acoustical properties (Burt et al., 1995; Guillaume et al., 2007; Wiese et al., 2004).

7.2 Earcons and auditory icons

Studies of non-verbal sounds used to convey information in user environments have to a large extent focused on two types of sound: earcons and auditory icons. The concept of earcons was introduced by Blattner, Sumikawa and Greenberg (1989). The researchers suggested that sound could be structured according to principles similar to those of visual icons. They defined earcons as “nonverbal audio messages used in the user-computer interface to provide information to the user about some computer object, operation, or interaction”. The authors suggested that earcons, like visual icons, could be divided into three classes: representational, abstract, and semi-abstract. Abstract earcons, see figure 6, use musical parameters to form unique sounds. By manipulating parameters such as timbre, register and rhythm, earcons with specific meanings can be created.

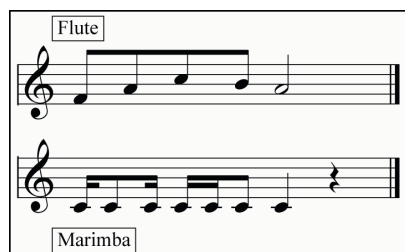


Figure 6 *Two examples of abstract earcons.*

Representational earcons, in contrast, are sounds that are already familiar to the user. Several other authors who have investigated the use of earcons have clearly focused on abstract earcons (e.g., Brewster, Wright & Edwards, 1993; McGookin, 2004). Brewster et al. (1993), for example, defined earcons as “abstract, synthetic tones that can be used in structured combinations to represent parts of an interface”.

Gaver (1986) introduced a concept rather similar to that of representational earcons, coining the term “auditory icons.” Gaver (1989) defined auditory icons as “everyday sounds meant to convey information about events in the computer by analogy with everyday events”. Gaver (1989) argued that people often listen to an event or a source of sound rather than to the sound per se. That is, that they hear the characteristics of the source rather than those of the sound. He refers to this mode of listening as “everyday listening”. The concept of everyday listening is consistent with Gibson’s (Gibson, 1979) ecological perspective on perception.

7.2.1 Auditory icons and earcons as warnings

Auditory icons make use of established associations between sound and what it represents. They are chosen because they are reasonably meaningful, familiar and relevant to the user. Their familiarity makes them easier to learn and better facilitates automatic information processing. Furthermore, auditory icons can communicate an inherent sense of urgency (based on the previous experiences of the listener with the sound), which in turn is likely to trigger appropriate urgency perception and emotional reactions. Accordingly, a great deal of research has shown that auditory icons yield faster response times and more accurate responses and are easier to learn than are other non-verbal sounds (e.g., Graham, 1999; McKeown, 2005; Vilimek & Hempel, 2005; Larsson et al., 2008).

Abstract earcons, in contrast, are associated with new rules for how to interpret sound. For instance, a specific musical timbre might be associated with a certain type of road danger. If the listener has not fully learned how to interpret the sound, information processing may be data limited and/or knowledge based. The process will therefore tend to be slow, demand greater mental resources and encourage user error.

However, with practise, the processing of new sounds can become more automated, and the driver can recognise the sound as indicating danger. Stanton & Edworthy (1998) compared a set of new environmental sounds (auditory icons) with existing conventional warnings in an intensive treatment unit. They found that the new sounds were more effective for novice users, who produced fewer errors in response to such sounds. However, the old warnings were more effective for experienced users.

One potential disadvantage of auditory icons is that they can lead to more inappropriate responses to nuisance warnings (Graham, 1999; Gray, 2011). Such inappropriate behaviour may indicate that these sounds are processed more automatically. It could also be argued that the familiarity triggers a direct emotional response, as suggested by the aforementioned emotional reaction model (Västfjäll et al., 2006); see figure 5.

7.3 Natural warning sounds

Ulfvengren (2003) introduced the concept of “natural warning sounds” for auditory warnings in aviation. A natural warning sound should meet the following requirements. It should:

- Have a natural meaning within the user’s context
- Be compatible with the auditory information process
- Be pleasant to listen to (not annoying)
- Be easy to learn
- Be easy to remember
- Be efficient for action
- Be efficient for compliance
- Decrease the time required to perform the task
- Contain relevant information

- Be clearly audible
- Be easily discriminated from other groups of alerts
- Be easily discriminated from other individual alerts

8 Situation awareness

Situation awareness (SA), a concept with roots in the field of aviation, has been presented as a fundamental contributing factor in decision making in dynamic systems (Wickens et al., 1999). This makes SA relevant to the present research in general and more specifically as an indicator of traffic safety.

There are many definitions of SA (Alfredsson, 2007). Endsley (1995) presents the following widely used definition: “Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future”. In other words, SA involves knowledge of the past, the present and the near future. Furthermore, Endsley (1995) states that SA involves goal-related knowledge. For example, a driver who perceives the movements of another vehicle should be aware of how his or her perceptions may affect driving safety.

Clearly, inadequate SA can have negative effects on traffic safety. If the driver is not aware of objects in the traffic environment, does not understand the intentions of other drivers or cannot make predictions about their future status, his or her lack of awareness could have negative consequences for decision making. However, awareness is not the only requirement for successful decision-making and performance. Drivers who lack an understanding of how to handle a situation can also make inappropriate decisions. Accordingly, Endsley’s model (Endsley, 1995) illustrates that SA supports decision making but is not tantamount to decision making. High SA does not guarantee appropriate decisions or performance, and low SA does not always lead to bad decisions or lower performance.

SA can be described with reference to various subcategories (Endsley, 1995). In the present thesis, focus is on driver SA with regard to safety-relevant objects in the traffic environment.

8.1 *Conclusions regarding situation awareness*

Auditory warnings can make drivers aware of events happening outside their visual field. For example, an appropriate sound can increase driver awareness of a school bus that has stopped out of sight over the next crest in a road.

In addition to correct SA, the speed at which SA develops is an essential factor in safety-critical situations. If the sound takes a long time to process, the driver may not have enough time to make a decision and appropriately respond to the situation.

Furthermore, although a sound may increase a driver’s awareness of a particular event on the road, it can also hinder driver awareness of other events. SA is a continuously updating state that requires continuous access to informational cues in the traffic environment. Endsley (2000) mentions the following threats to SA: attentional tunnelling, requisite memory trap, workload, anxiety, fatigue and other stress-inducing factors, data overload, misplaced salience, complexity creep, errant mental models and out-of-the-loop syndrome. Wickens et al. (1999) mentions the following four factors as influencing the quality of diagnosis and situation awareness: perception, attention, long-term memory and working memory. For example, if an auditory warning contributes to attentional narrowing, SA could decrease.

9 Summary of studies

9.1 Study 1

Aims

Study 1 examined the benefits and costs of three different types of sound (non-verbal meaningful sound, non-verbal arbitrary sound, and verbal sound) that were designed to enhance the awareness of commercial drivers in critical traffic situations. The primary aim was to examine the relative levels of cognitive effort associated with various sounds once the drivers had learned them. The differences in learnability and perceived annoyance for the different sound types were also investigated.

Methodology

Each sound type contained five different sounds. These sounds were presented in six spatial locations around the drivers and represented a total of 30 critical driving situations. For the meaningful sounds, we used the sounds that road objects use to get attention (e.g., we used a car horn to represent a car). These sounds would typically have been referred to as auditory icons in previous research. The arbitrary sounds were musical in nature and differed in terms of their timbre, melody and rhythm. These sounds would typically have been referred to as abstract earcons or simply earcons in previous research. The verbal sounds were keywords such as “truck” and “pedestrian” (in Swedish) that stated the name of the road object.

Eighteen truck drivers participated in the experiment. During a learning session, the drivers were allowed to practice on the three sound types until they felt comfortable with the intended meaning of the sounds. Both the learning time and the number of trials were monitored for each sound type. Cognitive effort was estimated using a dual-task setup in which drivers responded to sounds while performing a Lane Change Test (LCT). The drivers responded to the sounds using a touch screen that presented four driving situations simultaneously. Response accuracy and response speed was monitored to estimate cognitive effort. At the end of each driving session, the drivers rated their perceived annoyance and cognitive effort using a 7-point rating scale.

Results

The results clearly showed differences between the sound types with regard to learnability, cognitive effort and annoyance. The arbitrarily mapped sounds required more learning time and a greater number of trials compared to the other sounds. The arbitrarily mapped sounds were also associated with lower performance levels during the simulated driving task. In fact, all 18 drivers performed worse when exposed to the arbitrary sounds than when exposed to the other two types of sounds. The drivers also found the arbitrary sounds to be more annoying than the meaningful non-verbal and verbal sounds.

Contribution

Previous studies have shown that meaningful sounds (otherwise known as auditory icons) improve performance as measured using similar dependent variables as in the present study (e.g., Graham, 1999). However, although study 1 supports the conclusions of previous studies, it also contributes new information to our understanding of meaningful sounds and their impact.

First, the study shows that extended learning cannot easily compensate for arbitrary mapping between sounds and critical road events.

Second, although previous studies have advocated the use of auditory icons to provide in-vehicle

warnings, they have often focused on just a few driving situations (e.g., forward collision warnings). The present study used spatially presented auditory warnings to represent 30 different traffic events.

Third, the result show that annoyance may be higher for arbitrarily mapped sounds compared to meaningful sounds. Studies on annoyance and auditory warnings have primarily focused on the roles of acoustical parameters (urgency-related) and learned meaning. In contrast, the present study indicates that the level of annoyance also depends on the appropriateness of the mapping between the sound and what the sound represents. However, all sounds used in the study had unique acoustic properties, and these results do not eliminate the possibility that abstract warnings were perceived as more annoying because of their specific physical characteristics.

9.2 Study 2

Aims

Study 2 examined how the acoustic parameters of warnings influence annoyance among commercial drivers and impact the ability of those drivers to respond to events on the road that are unrelated to the warning. The study examined the following two main hypotheses:

1. Warning signals with a higher level of psychoacoustic urgency (conveyed by acoustic parameters) will be perceived as more annoying by commercial truck drivers.
2. Warnings that express higher levels of psychoacoustic urgency have a negative effect on truck drivers' ability to detect and respond to a subsequent, unpredictable change on the road ahead.

Methodology

Two warning signals were designed for this study that were used to warn drivers about pedestrians standing on the roadside. Both warnings started with a brief verbal message: "pedestrians" (in Swedish). The verbal message was followed by one of two patterns of tone bursts that were designed to express significantly different levels of urgency.

A stimulus evaluation was conducted (unrelated to the main experiment) to investigate the relative potential of the two warning sounds to trigger emotional reactions. It was found that the high-urgency warning was considered both more alarming and more annoying than the low-urgency warning.

The main experiment was conducted with 24 commercial drivers in the VTI Driving Simulator III in Linköping, Sweden. The drivers drove on a track for 25 to 30 minutes. Several times during each trial, unexpected critical events occurred only seconds after the drivers had been presented with an unrelated high-urgency or low-urgency warning. The drivers had to brake to avoid a collision. Brake response time and the force of each driver's response to the unrelated event were the main dependent driving variables in the study.

Results

Thirteen of the 24 drivers rated the high-urgency warning as more annoying than the low-urgency warning, and 9 drivers rated both auditory warnings as equally annoying. In addition, a negative correlation emerged between the degree of driving experience and the rated annoyance level of both warnings.

The drivers braked significantly harder (and tended to brake later) in the first critical driving situation after receiving a high-urgency warning than after receiving a low-urgency warning.

Contribution

Several studies (e.g., Marshall et al., 2007) have examined the relationship between the acoustical properties of warnings (which indicate the level of urgency) and the annoyance that those signals cause. Study 2 examined how such characteristics influence annoyance levels but it also considered another negative side effect of high-urgency warnings, their potential to negatively impact drivers ability to respond to unrelated events on the road. Thus, the results of study 2 complements those of previous studies that examined annoyance and response times, as associated with auditory warnings. The following two main conclusions can be drawn from the results:

First, the results support the notion that the acoustic parameters of a warning can impact driver responses to unexpected, unrelated events. Future research should examine the influence of acoustic parameters (which, again, are urgency related) on less experienced drivers.

Second, the results indicate that annoyance of auditory warnings in commercial vehicles cannot be predicted based on acoustical parameters alone. As has been proposed by other researchers, both annoyance and urgency ratings may depend on learnt meaning (e.g., McKeown, 2005), and annoyance may result when the sound interferes with ongoing cognitive tasks (Zimmer, 2008). The results of this study also indicate that annoyance ratings are related to driver experience.

9.3 Study 3

Aims

The results of study 1 suggest that meaningful sounds (auditory icons) can be less annoying than arbitrary mapped sounds. However, previous research has indicated that commercial drivers do not perceive auditory icons as serious warnings. Thus, the primary aim of study 3 was to examine the degree to which commercial drivers initially accepted auditory icons as warning signals. A secondary aim was to examine the underlying factors that affect the acceptance of auditory icons as warnings in trucks.

Methodology

Twenty-two commercial drivers participated in the evaluation. The trials were conducted inside a Scania R truck cabin. Two complementary methods were used to examine the acceptance of five auditory icons associated with critical driving situations.

The first method involved the use of a sound selection task. The drivers watched recorded videos of the different driving situations (projected in front of the cabin) and selected an auditory warning for each situation. The subjects could select one of three warning modes for each situation: no warning, a brief abstract auditory signal (arbitrarily mapped), or an abstract auditory signal and an auditory icon played in sequence. The participants were able to select one of 162 abstract sounds for each situation, but there was only one auditory icon for each driving situation.

Second, after the trial, the subjects rated the auditory icons for the five situations using a method presented by Van der Laan, Heino and De Waard (1996). The method involves the use of nine 5-point rating scale items for two values, “usefulness” and “satisfaction”.

Results

The results of the sound selection task showed that in two of the driving situations, 18 and 17 of the 22 drivers selected the auditory icon. In the other driving situations, only 5 to 7 participants selected the auditory icon.

The two most commonly selected auditory icons in the sound selection task received significantly higher usefulness and satisfaction scores than some of the other auditory icons. This was especially apparent for their usefulness scores.

A logistic regression analysis revealed that the usefulness and satisfaction scores were both significant predictors of selection in the sound selection task for three of the five auditory icons. The drivers that gave a sound a high score were more likely to select the sound in the selection task. Furthermore, strong positive correlations between usefulness and satisfaction scores were found for 4 of the 5 auditory icons.

Contribution

Study 3 shows that the initial acceptance of auditory icons as warning signals in commercial vehicles is generally neither high nor low; instead, acceptance varies significantly from one warning to the next in different driving situations. However, the results clearly show that the initial acceptance levels for these sounds can be high. Thus, developers should seriously consider using auditory icons as warnings in commercial vehicles instead of arbitrarily mapped sounds or simple beeps.

The study also offers some indications regarding why certain auditory icons are preferred or not as

warning signals. The results illustrate that if the drivers find a sound to be more useful (as employed by Van der Laan et al. (1996)), they are also more prone to select the sound for a warning system. The satisfaction associated with the auditory icons was also a predictor of the drivers' decisions in several driving situations. Therefore, the result confirms that an unpleasant experience (e.g., annoyance and unpleasantness) is often not considered an appropriate property for auditory icons, when the sounds are used to increase commercial drivers' awareness of safety critical events.

However, it is of limited help for practical warning design to know that perceived usefulness and satisfaction (as employed by Van der Laan et al. (1996)) are important characteristics of auditory icons used as warnings, unless we do not also know what it is that makes the sound perceived as useful and satisfactory. One interesting result (not mentioned in the paper) is that the two most frequently selected auditory icons, which also received the highest usefulness and satisfaction scores from drivers, were auditory icons that warned about dangers that were not perceived visually by the driver. In the other three critical situations, the danger appeared in the forward driving direction as a natural part of the situation. Thus, the results indicate that initial acceptance for auditory icons may be especially high when the sound increases awareness of dangers that would not otherwise be perceived visually.

9.4 Study 4

Aims

In study 4, a questionnaire was used to examine the opinions of vehicle developers and commercial drivers regarding properties of warnings that have been identified as potentially important in previous research. The motive of the examination was to identify helpful aspects of the developers' and drivers' opinions, using them to maximise the success of warning design and avoid some of its pitfalls. The following research questions were addressed:

1. Which attributes of auditory warning signals do vehicle developers and commercial drivers consider important?
2. Are there differences in the developers' opinions regarding warning signals of different levels of urgency?
3. Are there differences between the opinions of vehicle developers and those of professional drivers?

Methodology

The questionnaire was based on a previous survey conducted by Tan and Lerner (1995). The questionnaire was distributed to 50 developers working at Scania CV AB in Sweden and 76 commercial drivers working in Sweden. The response rate was 68 % for the developers and 54 % for the drivers.

The participants ranked nine warning attributes using a 5-point scale ranging from 1 (not at all important) to 5 (very important). The subjects provided ratings for both a low-urgency situation and a high-urgency situation.

In evaluating the low-urgency situation, the participants were instructed to imagine that a school bus had stopped 400 metres in front of their own vehicle. In evaluating the high-urgency situation, the participants were instructed to imagine that their own vehicle was about to collide with another vehicle or object.

Results

The results showed that both drivers and developers ranked most of the investigated attributes as very important. For example, both developers and drivers agree that it is important that auditory warnings are easy to understand and prepare the driver to respond.

For the developers, the perceived importance of seven of the nine investigated attributes differed significantly in the high-urgency situation versus the low-urgency situation. It is especially notable that 41 % of the developers rated it unimportant whether the high-urgency warning was annoying. In addition, 12 % of the developers rated it unimportant whether the high-urgency warning was too startling.

The results suggests that in a high-urgency situation, developers may find it especially important that the warning triggers an appropriate orienting response, that it prepares the driver to respond, that it is clearly audible, and that it is easy to distinguish from other sounds in the environment. In the low-urgency situation, the developers found it more important that the warning is not annoying to drivers, that it has an appropriate urgency level, that the driver accepts it, and that it is not too startling.

A number of significant differences emerged between ratings by developers and drivers. For example, drivers found it significantly more important that the high-urgency warning is not annoying.

Contribution

The results of study 4 illustrate the relationship between scientific findings regarding the attributes of auditory warnings and the subjective relevance of those findings for vehicle developers and commercial drivers. Some interesting overall findings emerged.

First, both groups recognised the importance of many of the investigated warning attributes. Given the vast number of studies that have asserted the importance of developing warnings that are easy to understand, it is especially interesting to see that both groups recognise this attribute as very important.

Second, the results show that developers may be prone to employ a “better safe than sorry” strategy, not seeking to avoid annoyance or even severe startling responses, when designing high-urgency auditory warnings. Similar strategies for warning design have been reported to occur in various user environments (Patterson, 1990).

Third, the results show in what ways developers may prioritise differently when designing auditory warnings for situations of different levels of urgency.

Forth, the study identified differences between the opinions of developers and those of professional drivers. These differences should be further investigated, and they also suggest that drivers should be involved in the process of designing auditory warnings.

10 Conclusions and implications

One objective of the present thesis was to examine the relationships between the characteristics of auditory warning signals in commercial vehicles and indicators of traffic safety. A second objective was to examine the opinions of system developers and commercial drivers regarding potentially important warning attributes. The main results and conclusions of the thesis are described below.

The role of context-specific meaning in sound

Study 1 support that sounds that are meaningful to drivers and have a relationship to the object or event that they represent can be effective warning signals. In comparison with arbitrarily mapped sounds, meaningful sounds (auditory icons) are easier to learn, support more rapid and more accurate situation awareness, and cause lower levels of annoyance. It seems like meaningful and relevant sounds, in combination with spatially distributed loudspeakers, allow drivers to easily learn and recognise a significant number of critical traffic situations, only based on the sound. The faster and more accurate processing observed for these sounds also indicates that drivers need to invest less mental resources when processing a warning. This should leave them more mental resources to navigate the critical driving situation.

Previous research has noted that commercial drivers may be sceptical about the use of auditory icons as warnings because they do not consider them to be serious warnings (Belz, Robinson & Casali, 1999). However, study 3 finds that initial acceptance rates for using auditory icons as warnings can be very high. Also, the study indicates that acceptance can be especially high for auditory icons that increase drivers' situation awareness about road dangers when such dangers may not be readily perceived visually through the traffic environment.

Warning properties and attention

Study 2 examined the relationships between the acoustic parameters of warnings and drivers ability to respond to events in the traffic scene that is unrelated to the warnings. The results do not support the view that more urgent auditory warnings increase drivers' response times to events in the traffic that is unrelated to the warning. However, the results suggest that researchers should continue to investigate the negative effects of high-urgency auditory warnings, especially their effects on less experienced and novice drivers.

Warning properties and annoyance

Previous research on annoyance associated with auditory warnings with particular design characteristics has, to a large extent, focused on the effects of acoustical parameters. The results of the studies presented here show that annoyance is a complex phenomenon that cannot be predicted based on acoustical parameters alone. This finding, in turn, indicates the importance of investigating the annoyance associated with warnings via studies of real commercial drivers, and preferable in their natural driving environment.

Because annoyance related to warning design can depend on several factors, it is insufficient to investigate the annoyance per se. It is also important to consider the underlying reason why the experience is unpleasant. Several factors that contribute to the annoyance associated with warnings may be more easily minimised (e.g., inappropriate mapping between the sound and the event), but others may be more difficult to address (e.g., annoyance related to the fact that warnings catch attention and indicate danger).

Study 4 points out that some developers are unconcerned about whether or not high-urgency warnings are annoying. These results are a bit worrying. If developers are unconcerned about

whether the sound is annoying (or even extremely startling) they may not aim to minimise the negative experience of these sounds, leading to a range of possible unnecessary negative effects. Some possible effects have been pointed out in this thesis, including increased driver workload (Wiese et al., 2004), more users turning the sound or warning system off (Block et al., 1999), more risk-taking drivers (King & Parker, 2008), and potentially more attention directed towards the annoying system rather than the road.

Study 4 supports the notion that commercial drivers, in comparison with vehicle developers, find it significantly more important that high-urgency warnings informing them about traffic events are not annoying. Furthermore, study 3 indicates that drivers often consider an unpleasant experience to be a negative quality for warnings (auditory icons) that are designed to increase their situation awareness.

Opinions of developers and drivers about warning attributes

Study 4 illustrates that according to both vehicle developers and professional drivers, there exists a range of potentially important attributes of auditory warnings. It is especially promising and quite interesting to see that both groups recognise that warnings should be easy to understand.

Also, study 4 shows how developers may prioritise differently when designing warnings for situation of different levels of urgency. In a high-urgency situation, they found it especially important that the warning triggers an appropriate orienting response, that it prepares the driver to respond, that it is clearly audible, and that it is easy to distinguish from other sounds in the environment. In the low-urgency situation, they rated it especially important that the warning is not annoying, that it has an appropriate urgency level, that the driver accepts the warning, and that it is not too startling.

The differences found between developers and drivers' opinions for some of the warning attributes suggest that drivers should be invited to take part in the design process of auditory warnings.

11 Two new design tools

A significant body of research has involved investigating the effects of auditory warnings on humans in general and in different types of user contexts. Nevertheless, considering the present state of knowledge in the field, it is difficult to predict what sound will be the best for a specific warning function or driving situation. Research has identified a number of potentially important attributes of auditory warnings that should be considered when auditory warnings are implemented in vehicles. However, it remains the responsibility of the system developers to design the sound and test whether it possesses the appropriate attributes in its unique context.

Even though developers recognise the importance of warning attributes (as noted in study 4), they do not necessarily know how to design the warnings or how to conduct tests to investigate the appropriateness of the warnings. Currently, there is a lack of audio design processes and tools that are specifically designed to help vehicle developers in this area. In an effort to facilitate vehicle system developers, the present research project has been involved in the development of two new audio design tools. One tool is a design process that has been specifically adapted for the design of in-vehicle auditory warnings. The second tool is a web-based interface called the Participatory Audio Research Tool (PART), which can be used to gather the opinions of end-users (e.g., drivers) on auditory cues (e.g., in-vehicle auditory warnings). Both of these tools are described in the Appendix.

12 References

- Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis & Prevention*, 27(5), 707-715.
- Alfredson, J. (2007). *Differences in situational awareness and how to manage them in development of complex systems* (Doctoral dissertation). Linköping University, Sweden.
- Anderson, A. K., & Phelps, E. A. (2001). Lesions of the human amygdala impair enhanced perception of emotionally salient events. *Nature*, 411, 305-309.
- Baddeley, A. D., Logie, R., Nimmo-Smith, I., & Brereton, N. (1985). Components of fluent reading. *Journal of Memory and Language*, 24, 119-131.
- Belz, S. M., Robinson, G. S., & Casali, J. G. (1999). A new class of auditory warning signals for complex systems: auditory icons. *Human Factors*, 41(4), 608-618.
- Berglund, B., & Preis, A. (1997). Is perceived annoyance more subject-dependent than perceived loudness? *Acustica*, 83, 313-319.
- Björnstig, U., Björnstig, J., & Eriksson, A. (2008). Passenger car collision fatalities - with special emphasis on collisions with heavy vehicles. *Accident Analysis and Prevention*, 40, 158-166.
- Blattner, M. M., Sumikawa, D. A., & Greenberg, R. M. (1989). Earcons and icons: Their structure and common design principles. *Human-Computer Interaction*, 4, 11-44.
- Block, F. E., Nuutinen, L., & Ballast, B. (1999). Optimization of alarms: a study on alarm limits, alarm sounds, and false alarms, intended to reduce annoyance. *Journal of clinical monitoring and computing*, 15, 75-83.
- Booher, H. R. (1978). Effects of visual and auditory impairment in driving performance, *Human Factors*, 20(3), 307-320.
- Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1), 49-59.
- Brewster, S., Wright, P. C., & Edwards, A. (1993). An Evaluation of Earcons for Use in Auditory Human-Computer Interfaces. In S. Ashlund (Ed.), *Conference on Human Factors in Computing Systems*. Amsterdam: IOS Press.
- Brown, I. D., Tickner, A. H., & Simmonds, D. C. V. (1969). Interference between concurrent tasks of driving and telephoning. *Journal of applied psychology*, 53(5), 419-424.
- Burt, J. L., Bartolome, D. S, Burdette, D. W., & Comstoc, J. R. (1995). A psycho physiological evaluation of the perceived urgency of warning signals. *Ergonomics*, 38(11), 2327-2340.
- Chapman, P. R., & Underwood, G. (1998). Visual search of driving situations: Danger and experience. *Perception*, 27, 951-964.

- Christianson, S. A., Loftus E. F., Hoffman, H., & Loftus G. R. (1991). Eye fixations and memory for emotional events. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17(4), 693-701.
- Cowan, N. (1995). *Attention and Memory: An integrated framework*. Oxford: Oxford University Press.
- Deffenbacher J. L., Lynch R. S., Oetting E. R., & Yingling D. A. (2001). Driving anger: correlates and a test of state-trait theory. *Personality and Individual Differences*, 31, 1321-1331.
- Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J., Perez, M. A., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z. R., Jermeland, J., & Knipling, R. R. (2006). *The 100-Car Naturalistic Driving Study, Phase II - Results of the 100-Car Field Experiment* (Report No. DOT HS 810 593). Washington, DC: National Highway Traffic Safety Administration.
- Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behaviour. *Psychological Review*, 66, 183-201.
- Edworthy, J., Loxley, S., & Dennis, I. (1991). Improving Auditory Warning Design: Relationship between Warning Sound Parameters and Perceived Urgency. *Human Factors*, 33(2), 205-231.
- Edworthy, J., & Adams, A. (1996). *Warning design: A research perspective*. London: Taylor & Francis Ltd.
- Ellermeier, W., Zeitler, A., & Fastl, H. (2004). Predicting annoyance judgements from psychoacoustic metrics: Identifiable versus neutral sounds. Paper presented at the 33rd international congress and exposition on noise control engineering, Prague, Czech Republic.
- Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, 37(1), 32-64.
- Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement*. Mahwah: LEA.
- Estes, Z., & Verges, M. (2008). Freeze or flee? Negative stimuli elicit selective responding. *Cognition*, 108, 557-565.
- Freedman, M., Lerner, N., Zador, P., Singer, J., & Levi, S. (2009). *Effectiveness and Acceptance of Enhanced Seat Belt Reminder Systems: Characteristics of Optimal Reminder Systems* (Report No. DOT HS 811 097). Washington, DC: National Highway Traffic Safety Administration.
- Fucci, D., Petrosino, L., Hallowell, B., Andra, L., & Wilcox, C. (1997). Magnitude estimation scaling of annoyance in response to rock music: Effects of sex and listeners preference. *Perceptual and Motor Skills*, 84, 663-670.
- Gaver, W.W. (1986). Auditory icons: Using sound in computer interfaces. *Human-Computer Interaction*, 2, 167-177.
- Gaver, W.W. (1989). The SonicFinder: An Interface that Uses Auditory Icons. *Human-Computer Interaction*, 4, 67-95.

- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
- Graham, R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application. *Ergonomics*, 42(9), 1233-1248.
- Gray, R. (2011). Looming auditory collision warnings for driving. *Human Factors*, 53(1), 63-74.
- Gross, J. J. (2001). Emotion regulation in adulthood: timing is everything. *Current Directions in Psychological Science*, 10(6), 214-219.
- Guillaume, A., Drake, C., Rivenez, M., Pellieux, L., & Chastres, V. (2002). Perception of urgency and alarm design. Paper presented at the International Conference on Auditory Display 2002, Kyoto, Japan.
- Haas, E. C., & Edworthy, J. (1996). Designing urgency into auditory warnings using pitch, speed and loudness. *Computing & Control Engineering Journal*, 7(4), 193-198.
- Hale, A. R., Stoop, J., & Hommels, J. (1990). Human error models as predictors of accident scenarios for designers in road transport systems. *Ergonomics*, 33, 1377-1387.
- Hellier, E. J., Edworthy, J., & Dennis, I. (1993). Improving auditory warning design: quantifying and predicting the effects of different warning parameters on perceived urgency. *Human Factors*, 35(4), 693-706.
- Hiramatsu, K., Takagi, K., & Yamamoto, T., & Ikeno, J. (1978). The effect of sound duration on annoyance. *Journal of sound and vibration*, 59(4), 511-520.
- Hollnagel, E. (2002). *Cognition as control: A pragmatic approach to the modelling of joint cognitive systems*. Retrieved September 13, 2011, from http://www.ida.liu.se/~eriho/images/IEEE_SMC_Cognition_as_control.pdf
- Horrey, W. J., & Wickens, C. D. (2006). Examining the Impact of Cell Phone Conversations on Driving Using Meta-Analytic Techniques. *Human Factors*, 48(1), 196-205.
- Juslin, P. N., & Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *Behavioural and Brain Sciences*, 31, 559-621.
- Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs: Prentice-Hall.
- King, Y., & Parker, D. (2008). Driving violations, aggression and perceived consensus. *European Review of Applied Psychology*, 58(1), 43-49.
- Khan, M. S., Johansson, Ö., & Sundback, U. (1997). Development of an annoyance index for heavy-duty diesel engine noise using multivariate analysis. *Noise Control Engineering Journal*, 45(4), 157-167.
- Kjellberg, A., Landström, U., Tesarz, M., Söderberg, L., & Åkerlund, E. (1996). The effects of nonphysical noise characteristics, ongoing task and noise sensitivity on annoyance and distraction due to noise at work. *Journal of Environmental Psychology*, 16, 123-136.

- Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data* (Report No. DOT HS 810 594). Washington, DC: National Highway Traffic Safety Administration.
- Landström, U., Åkerlund, E., Kjellberg, A., & Tesarz, M. (1995). Exposure Levels, Tonal Components and Noise Annoyance in Working Environments, *Environment International*, 21(3), 265-275.
- Larsson, P., Opperud, A., Fredriksson, K., & Västfjäll, D. (2009). Emotional and behavioral response to auditory icons and earcons in driver-vehicle interfaces. Paper presented at the 21st (ESV) international technical conference on the enhanced safety of vehicles, Stuttgart, Germany.
- Lee, J. D., Young K. L., & Reagan, M. A. (2008). Defining driver distraction. In J.D. Lee, K.L. Young & M.A. Reagan (Eds.), *Driver distraction, - Theory, Effects, and Mitigation*. London: Taylor & Francis Ltd.
- Marshall, D. C., Lee, J. D., & Austria, P. A. (2007). Alerts for in-vehicle information systems: annoyance, urgency and appropriateness. *Human Factors*, 49(1), 145-157.
- McCarley, J. S., Vais, M. J., Pringle, H., Kramer, A. F., Irwin, D. E., and Strayer, D. L. (2004). Conversation Disrupts Change Detection in Complex Traffic Scenes. *Human Factors*, 46(3), 424-436.
- McGookin, D. (2004). *Understanding and Improving the Identification of Concurrently Presented Earcons* (Doctoral dissertation). University of Glasgow, UK.
- McKenna, F. P. & Farrand, P. (1999). The role of automaticity in driving. In G. B. Grayson (Ed.), *Behavioural Research in Road Safety IX*. Crowthorne: Transport and Road Research Laboratory.
- McKnight, A. J., & McKnight, A. S. (1993). The effect of cellular phone use upon driver attention. *Accident Analysis & Prevention*, 25(3), 259-265.
- Michon, J. A. (1985). A critical view of driver behavior models: what do we know, what should we do? In L. Evans & R. C. Schwing (Eds.), *Human behavior and traffic safety*. New York: Plenum Press.
- National Highway Traffic Safety Administration. (2008). *Traffic Safety Facts 2008 Data* (Report No. DOT HS 811 158). Washington DC: National Highway Traffic Safety Administration.
- Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource limited processes. *Cognitive Psychology*, 7, 44-64.
- Olson, R. L., Hanowski, R. J., Hickman, J. S., and Bocanegra, J. (2009). *Driver distraction in commercial vehicle operations* (Report No. FMCSA-RRR-09-042). Washington, D.C.: Federal Motor Carrier Safety Administration.
- Patten, C. J. D., Kircher, A., Östlund, J., & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis & Prevention*, 36(3), 341-350.

- Patten, C.J.D., Kircher, A., Östlund, J., Nilsson, L., & Svensson, O. (2006). Driver experience and cognitive workload in different traffic environments. *Accident Analysis & Prevention*, 38, 887-894.
- Patterson, R. D. (1990). Auditory warning sounds in the work environment. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 327, 485-492.
- Pizzighello, S., & Bressan, P. (2008). Auditory attention causes visual inattentive blindness. *Perception*, 37, 859-866.
- Pratto, F., & Oliver, P. J. (1991). Automatic vigilance: The attention-grabbing power of negative social information. *Journal of Personality and Social Psychology*, 61(3), 380-391.
- Ranney, T. A. (1994). Models of driving behavior: A review of their evolution. *Accident Analysis and Prevention*, 26, 733-750.
- Rasmussen, J. (1983). Skills, Rules and Knowledge; Signals, Signs and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on systems, man, and cybernetics*, 13(3), 257-266.
- Remington N. A., Fabrigar L. R., & Visser P. S. (2000). Reexamining the Circumplex Model of Affect. *Journal of Personality and Social Psychology*, 79(2), 286-300.
- Richard, C. M., Wright, R. D., Ee, C., Prime, S. L., Shimizu, Y., & Vavrik, J. (2002). Effect of a concurrent auditory task on visual search performance in a driving-related image-flicker task. *Human Factors*, 44(1), 108-119.
- Rumar, K. (1990). Driver requirements and road traffic informatics. *Transportation*, 17, 215-229.
- Russell, J. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology*, 39, 1161-1178.
- Shelton, J. T., Elliot, E. M., Eaves, S. D., & Exner, A. L. (2009). The distracting effects of a ringing cell phone: An investigation of the laboratory and classroom setting. *Journal of Environmental Psychology*, 29(4), 513-521.
- Stanton, N., & Edworthy, J. (1998). Auditory affordances in the intensive treatment unit. *Applied Ergonomics*, 29(5), 389-394.
- Strandroth, J. (2009). In-depth analysis of accidents with heavy goods vehicles - Effects of measures promoting safe heavy goods traffic. Borlänge: Swedish Road Administration.
- Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Current Directions in Psychological Science*, 16 (3), 128-131.
- Suied, C., Susini, P., & McAdams, S. (2008). Evaluating warning sound urgency with reaction times. *Journal of Experimental Psychology: Applied*, 14(3), 201-212.

- Tan, A. K., & Lerner, N. D. (1995). *Multiple attribute evaluation of auditory warning signals for in-vehicle crash avoidance systems* (Report No. DOT HS 808 535). Washington, DC: National Highway Traffic Safety Administration.
- Taylor, S. M. (1984). A path model of aircraft noise annoyance. *Journal of Sound and Vibration*, *96*(2), 243-260.
- Treffner, P., & Barrett, R. (2004). Hands-free mobile phone speech while driving degrades coordination and control. *Transportation Research Part F*, *7*, 229-246.
- Ulfvengren, P. (2003). *Design of Natural Warning Sounds in Human-Machine Systems* (Doctorial dissertation). Royal Institute of Technology, Sweden.
- Weltman, G., Smith, J. E., & Egstrom, G. H. (1971). Perceptual Narrowing During Simulated Pressure-Chamber Exposure. *Human Factors*, *13*(2) 99-107.
- Wickens, C. D. (1980). The structure of attentional resources. In R. S. Nickerson (Ed.), *Attention and Performance VIII*. Hillsdale: Erlbaum.
- Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159-177
- Wickens, C. D., & Hollands, J. G. (1999). *Engineering Psychology and Human Performance* (3rd ed.). Upper Saddle River: Prentice Hall.
- Wiese, E. E., & Lee, J. D. (2004). Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance. *Ergonomics*, *47*(9), 965-986.
- Van der Laan, J.D., Heino, A., & De Waard, D. (1996). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research C*, *5*(1), 1-10.
- Vilimek, R., & Hempel, T. (2005). Effects of speech and non-speech sounds on short-term memory. Paper presented at the International Conference on Auditory Display 2005, Limerick, Ireland.
- Västfjäll, D., Larsson, P., Genell, A., Sköld, A. and Kleiner, M. (2006). A neuropsychological theory of sound design: Implications for auditory icon in vehicles. In *Proceedings of the 2nd ISCA/DEGA Tutorial and Research Workshop on Perceptual Quality of Systems* (pp. 23-25). Bonn: International Speech Communication.
- Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, *18*, 459-482.
- Young, R. (2011, June). Driving consistency errors overestimate crash risk from cellular conversation in two case-crossover studies. Paper presented at the 6th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Lake Tahoe, USA.

Zimmer, K., Ghani, J., & Ellermeier, W. (2008). The role of task interference and exposure duration in judging noise annoyance. *Journal of Sound and Vibration*, *311*, 1039-1051.

APPENDIX: The new design tools

TOOL 1: A new design process for in-vehicle auditory warnings

The aim in developing the present tool has been to create a user-centred design process for the development of in-vehicle auditory warnings. That is, the intention has been to create a design process that is especially adapted for the design of warnings in the automotive industry and that can be used by developers of various types of in-vehicle systems.

The development of the design process

The design process for auditory warnings presented by Ulfvengren (2003) was the starting point for the development of the present design process. Ulfvengren's proposed design process is one of a few user-centred design processes for auditory warnings that have been published. The approach is based on a previous design process suggested by Stanton and Edworthy (1998), which, in turn, is based on a standardised method for evaluating public information systems (ISO/DIS 7001, 1979).

Shaping the new design process was conducted in collaboration with eight developers working with different aspects of sound and system design at the Swedish truck manufacturer company Scania CV AB. During two focus group interviews and one workshop (each meeting lasted approximately 90 minutes), various aspects of the design process were discussed.

The first focus group interview and the following workshop focused on the following three main questions:

1. What are the important attributes of auditory warnings for in-vehicle systems?
2. What tests should be used to examine the appropriateness of the auditory warnings?
3. In what order should the tests be conducted when they are performed as parts of an in-vehicle system development process?

In the workshop following the first interview, the developers were divided into two groups. Each group was asked to make suggestions about how to test potentially important attributes of auditory warnings and in what order those tests should be conducted. A major conclusion derived from the workshop was that developers found it challenging to identify what specific tests to use when investigating various warning attributes. However, the developers offered ideas regarding when tests could be performed as a part of the design process of in-vehicle systems.

After the workshop the moderator created a first prototype for a design process. The structure of the process was similar to the iterative process suggested by Ulfvengren (2003); however, the prototype contained a number of new steps and specified the context in which to test in-vehicle warnings. The prototype design process was then presented to the participants during the second focus group interview. In this interview, the vehicle developers were invited to contribute ideas about how the process might be changed and further refined to make it as useful as possible when designing in-vehicle systems. Several aspects of the prototype process were changed according to the participants' suggestions after the interview.

The current version of the process

The most recent version of the design process is presented in figure 1. The process is iterative, which means that the various steps may be repeated several times. It also means that it is likely that

many sounds that enter the design process will not remain throughout the entire process.

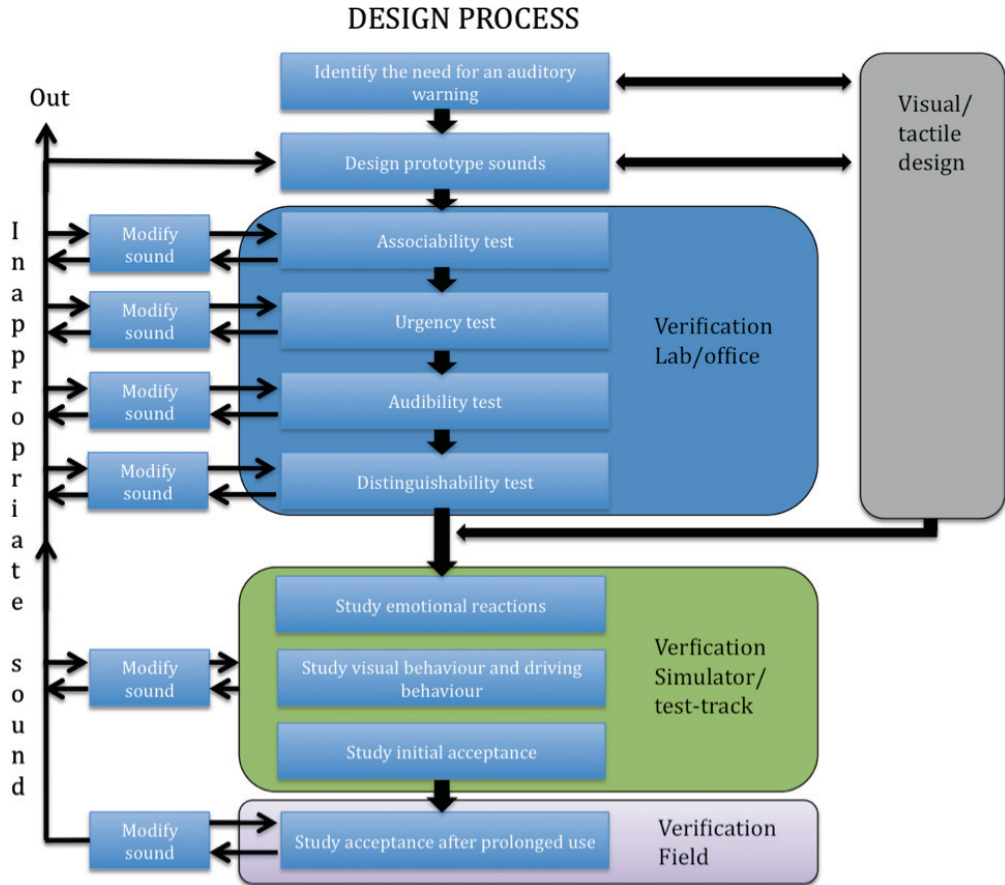


Figure 1 The current version of the design process.

The process is divided into ten steps. The first step is a requirement analysis, which is followed by development of prototype sounds. As indicated in the process, decisions made in these two first steps are incorporated, along with design decisions for other sensory modalities. For example, it might be decided to use a certain combination of sensory modalities to warn the driver. The development of prototype sounds is followed by four individual tests that are conducted to test the appropriateness of the prototype sounds. These four tests are performed on the auditory part of a warning, even though the intention is to use a multimodal solution. Thereafter, the suitability of complete warning solutions (sound or multimodal) is investigated using a driving simulator and/or test-track. Finally, the driver's acceptance of the warnings is investigated after prolonged use. The ten steps of the process are described in more detail below.

Step 1 - Identify the need for an auditory warning

In the future, decisions regarding whether to use sound to warn drivers may become increasingly determined by legislative demands. Currently, however, it is almost entirely the responsibility of the

vehicle developers to decide whether or not to use sounds as warnings in ITS. A good starting point for such decisions may be the guidelines that have been published regarding the suitability of sounds for different types of driving situations and for providing information; see Campbell et al. (2006). Furthermore, in a user-centred design process, it is preferable that the need for a warning sound be determined by considering the opinions of end-users, i.e., drivers.

Step 2 – Design prototype sounds

In this step, a number of prototype warning sounds are designed. This step may involve decisions regarding what type of sound to use (e.g., speech or non-speech sound). Primarily, this step addresses the free generation of ideas, and therefore, no precise method needs to be followed. However, a number of possible instruments exist involving users that may be helpful, such as the Rich Use Scenario (Pirhonen et al, 2006), Vocal Sketching and Metaphorical Sound Design (Hatch & Pirhonen, 2011). The Participatory Audio Research Tool, which is presented later in this appendix, may be another valuable tool for gathering opinions about possible designs from drivers.

Step 3 – Associability test

The aim of an associability test is to test how easily sounds can be associated with a dangerous situation. This stage may involve a learning test, i.e., a test that investigates the number of trials needed to learn the meaning of the sounds. Another method that may prove to be useful is a so-called sound-imagery test (Ulfvengren, 2003), in which the participants begin by pairing individual sounds with a range of possible meanings. Then, the participants rate the strength of those sound-meaning mappings. The results provide both an objective and a subjective measure of the strength of the sound-meaning mapping.

Step 4 – Urgency test

This stage aims to investigate whether the perceived urgency level of the sound corresponds well to the urgency of the situation. One easy way to conduct such a test is to allow drivers to rate both the urgency of the sound and the urgency of the situation and then compare the two results. Ratings of the perceived urgency can also be complemented with ratings of emotional reactions to the sounds (arousal and valence), which can be conducted by using the Self-Assessment Manikin presented by Bradley and Lang (1994).

Step 5 – Audibility test

An auditory warning may be completely or partially masked by other sound sources, such as tires, the wind, the engine, the radio or other sounds from in-vehicle systems. The aim of an audibility test is to investigate whether the sound, or important parts of the sound, could be masked by other sound sources. Recordings of the sound environment may be analysed, along with the auditory signal, to identify where in the frequency range problems may arise. Typical responses to a masking problem would be to decide whether to change the intensity or frequency content of the auditory signal or to attempt to reduce/remove the masking sound source. For example, muting the radio when a warning is played could be one way to remove a masking sound.

Step 6 – Distinguishability test

The aim of this test is to investigate to what extent an auditory cue can be distinguished from other auditory signals inside the vehicle. One approach to such an investigation would be to analyse existing auditory signals to identify any sound that has acoustic or semantic similarities with the

prototype sound. If any significant similarities are found, a listening test should be conducted to investigate to what extent drivers confuse the sounds.

Step 7 – Study emotional reactions

The aim of this test is to investigate drivers' affective responses when they receive a warning and experience the dangerous situation. For example, too low or too high arousal levels may not be appropriate, depending on the characteristics of the driving situation. Furthermore, negative emotions may signify an inappropriate warning design. Drivers' emotional reactions can provide valuable input to decisions about whether the auditory cue should be replaced, with the goal of impacting their affective state in a different way. One way to conduct this investigation would be to allow drivers to rate their emotional reaction immediately after they experienced the dangerous situation by using the Self-Assessment Manikin (Bradley et al., 1994).

Step 8 – Study visual behaviour and driving behaviour

This test aims to investigate drivers' visual behaviour and driving behaviour after a warning has been triggered. Common driving variables that are often of interest in an urgent situation, and that are relevant for warning effectiveness, are response time and accuracy of response. Depending on the situation, it might be relevant from a safety perspective to also investigate other driving variables, such as lateral position on the road. Visual behaviour is studied to determine whether the warning causes drivers to scan the appropriate areas of the driving scene after they receive a warning. The visual behaviour can be measured using either eye-tracking or head-tracking technology.

Step 9 – Study initial acceptance

A simulator study offers drivers the possibility to experience the sounds during relatively realistic circumstances. This capability, in turn, offers opportunities to study drivers' initial acceptance of the warnings. One way to accomplish this is by using the established method based on subjective rating items suggested by Van der Laan, Heino and De Waard (1996). However, we recommend that the subjective quantitative ratings should be complemented with a qualitative interview. An interview that asks drivers to explain why they perceived the sound in a certain way can provide developers with a better understanding of how eventual problems related to acceptance of the sound can be minimised.

Step 10 - Study acceptance after prolonged use

The ITS development process may allow developers to test the acceptance by users of the warning signals after prolonged use. For example, field tests may be conducted on an in-vehicle system for longer periods of time to examine the reliability of the system. In such an acceptance test, it is preferable to use the same method that was used when examining the initial acceptance of the warning. Using the same method allows developers to compare the results between tests and to draw conclusions regarding how acceptance of the warning is affected by extended use of the system.

Some final remarks

Following the suggested design process does not guarantee that the best auditory warning will be found. However, working according to the process would require in-vehicle system developers to consider many potentially important attributes of auditory warnings. Furthermore, the process offers

a structure that developers can follow when they are involved in an ITS development process. With these aspects taken together, following the process should minimise the risk that inappropriate auditory warnings are implemented in the driver's environment.

The process should not be considered to be a final version. Rather, it should be seen as a foundation or base that can be further developed and adapted as new insights in warning design are gained. Furthermore, the process has not yet been tested in a real design case. Such tests may reveal new ways in which the design process should be changed.

TOOL 2: PART – An application to gather end-users’ opinions

The Participatory Audio Research Tool (PART) is a system that has been developed at the Interactive Institute - Sonic Studio in Sweden. The following description of the tool is based on a more extended description provided by Fagerlönn and Liljedahl (2009). The main goal of PART is to facilitate system developers to gather opinions from end-users regarding sound design for specific user situations. The tool draws together the user (e.g., a commercial driver), the context (e.g., a critical driving situation) and the sound (e.g., a warning) to find a sound design that is optimal for a specific situation.

PART shares some fundamental ideas with the research tool Relations Between Musical Parameters and Perceived Properties (REMUPP), an application that was developed by Interactive Institute–Sonic Studio and that has been previously evaluated in the field of music pedagogy. Like REMUPP, the idea of PART is to allow the participants to respond to an experience using the medium of sound itself, without the need to translate the sound into other modes of expression (e.g., words). Instead, the user is given control over the auditory stimuli and is encouraged to modify the sound to adapt to one or more user situations.

There are some potential benefits for having the participants make judgements on the basis of sound (rather than words). Sound design may be challenging to discuss, especially for people who lack knowledge in the area and who are not conversant in the common terminology. Experienced users are likely to be able to identify and judge various user situations appropriately and insightfully. However, these users are not necessarily able to easily suggest modifications to sound designs on a detailed level. Accordingly, PART does not require any experience or knowledge in sound design.



Figure 2 Participatory Audio Research Tool (PART). The user situations are represented by images or videos. By using the radio buttons in the lower part of the screen, users can adapt the sound to the situation.

Implementation

The PART system consists of a client-server application. The client side has two main interfaces. One interface is used by developers and researchers to prepare test sessions (e.g., by uploading videos and sound files) and to extract data for statistical analysis. The other interface (see figure 2) is used by the participants to select sounds that they consider appropriate to user situations.

A user situation is represented in the interface by an image or video. The participants can select among user situations that are represented by the tabs to the right of the presented situation. The radio buttons at the bottom of the interface are used to select sounds for the situations. The buttons are organised in columns, and each column corresponds to a specific sound parameter. For example, changing the button configuration in one column may change the speed of the sound, while the other parameters of the sound are kept constant. If a user situation is represented by a video, the participant can also decide at what point in the course of the situation the sound should be played. This feature can be used, for example, when gathering drivers' opinions about the appropriate timing of a warning.

The investigated sound parameters, and the ways in which the parameters can be changed, can be referred to as an "audio design space". That is, the participants are given some control over the auditory stimuli but only within the limits determined by the constructed design space.

It is important to emphasise that the PART system does not actually modulate the sounds. The idea is that the interface gives the participants the impression that they are modulating certain parameters of the sound. However, all possible variations need to be rendered beforehand and uploaded as sound files to the system server.

Possibilities and limitations of use

PART can be used in various stages in a sound design process in which the subjective opinions of users are to be collected. For example, the tool can be employed in situations in which drivers are invited to give their opinions on auditory warnings for specific user situations. Another interesting application would be to offer end-users the ability to personalise their own sounds for systems in their personal working environment (e.g., a truck cabin). A third possible use of the system is for scientific investigations that aim to increase our understanding of the relationships between sound properties and characteristics of user situations. In a scientific study, the system can be used alone, or it can be used in combination with a more traditional listening test to produce higher confidence results.

End-users of systems and interfaces might be found in various parts of the world. PART was intentionally developed to be a web-based application, which allows for the rapid investigation of global similarities as well as cultural differences. Certainly, performing studies over the Internet may be problematic in terms of control, and developers would need to make the necessary arrangements to minimise confounding variables and to support test validity.

The ways in which sounds are structured in the design space of PART offer some practical limitations. For example, providing users with a "design space" with three sound parameters in four steps will require 64 sound files to be uploaded to the system. However, six sound parameters in four steps will require 4096 sound files. Consequently, PART may be best suited for investigations in which system developers have a general idea about what sounds to use but want to gather the opinions of end-users regarding some particular aspects of the sound (e.g., different beginnings and ends of the sound).

REFERENCES

- Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1), 49-59.
- Campbell, J. L., Richard, C. M., Brown, J. L., & McCallum, M. (2007). *Crash warning system interfaces: human factors insights and lessons learned* (Report No. HS 810 697). Washington, DC: National Highway Traffic Safety Administration.
- Fagerlön, J., & Liljedahl, M. (2009). Designing a web-based tool that informs the audio design process. In S. Ystad, M. Aramaki, R. Kronland-Martinet & K. Jensen (Eds.), *Auditory Display: 6th Interantional Symposium, CMMR/ICAD 2009*. Berlin: Springer-Verlag.
- Hatch, W., & Pirhonen, A. (2011). Designing alarm sounds for the control of a hydraulic platform. In *Proceedings of the 6th Audio Mostly - a Conference on Interaction With Sound* (pp. 116-121). Coimbra: University of Coimbra.
- Pirhonen, A., Murphy, E., McAllister, G., & Yu, W. (2006). Non-speech sounds as elements of a use scenario: a semiotic perspective. In *Proceedings of the 12th International Conference on Auditory Display* (pp. 134-140). London: Queen Mary, University of London.
- Stanton, N., & Edworthy, J. (1998). Auditory affordances in the intensive treatment unit. *Applied Ergonomics*, 29(5), 389-394.
- Ulfvengren, P. (2003). *Design of Natural Warning Sounds in Human-Machine Systems* (Doctorial dissertation). Royal Institute of Technology, Sweden.
- Van der Laan, J. D., Heino, A., & De Waard, D. (1996). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research C*, 5(1), 1-10.

PAPER 1

Fagerlönn, J., & Alm, H. (2010). Auditory signs to support traffic awareness. *IET Intelligent Transport Systems*, 4(4), 262-269.

This paper is a postprint of a paper submitted to and accepted for publication in IET Intelligent Transport Systems and is subject to Institution of Engineering and Technology Copyright. The copy of record is available at IET Digital Library.

Auditory signs to support traffic awareness

J. Fagerlönn¹ & H. Alm²

¹Interactive Institute – Sonic Studio, Piteå SE-94128, Sweden

²Department of Human Work Science, Luleå University of Technology, Luleå SE-94187, Sweden

Abstract: In-vehicle information systems (IVIS) may contribute to increased levels of cognitive workload, which in turn can lead to a more dangerous driving behaviour. An experiment was conducted to examine the use of auditory signs to support drivers' traffic situation awareness. Eighteen experienced truck drivers identified traffic situations based on information conveyed by brief sounds. Aspects of learning, cognitive demand and pleasantness were monitored and rated by the drivers. Differences in cognitive effort was estimated using a dual-task set-up, in which drivers responded to auditory signs while simultaneously performing a simulated driving task. As expected, arbitrary sounds required significantly longer learning times compared to sounds that have a natural meaning in the driving context. The arbitrary sounds also resulted in a significant degradation in response performance, even after the drivers got a chance to learn the sounds. Finally, the results indicate that the use of arbitrary sounds can negatively impact driver satisfaction. These results have implications for a broad range of developing intelligent transport systems designed to assist drivers in absence of fundamental visual information or in visually demanding traffic situations.

1 Introduction

Technical development of intelligent transport systems (ITS) is often associated with expectations of their potential to increase traffic safety [1]. But systems designed to give information could potentially disrupt the driver's ability to maintain full attention on the driving task. This in turn may lead to a more dangerous driving behaviour [2–4] and increase the risk of traffic accidents [5]. Additional tasks might be especially problematic in urgent, unusual and complex situations that already put high demands on the driver's limited attentional resources.

Presenting information visually may not be optimal. Researchers have reported that increased visual load can have negative effects on both detection performance [6] and lane keeping [3]. Thus, interfaces that allow the driver to keep their eyes on the road, such as combined visual and auditory solutions, can be more appropriate from a safety point of view. But research has also demonstrated that involvement in non-visual tasks can have a negative impact on safety. Engström et al. [3] found that an auditory continuous memory task resulted in increased gaze concentration towards the road centre. Numerous studies have reported negative effects of mobile phone conversation on workload and attention [2, 4, 7].

However, being involved in a verbal conversation is not the same as listening to sounds. McCarley et al. [8] concluded that the negative impact on visual search seen during natural telephone conversation was most likely due to speech reproduction. On the other hand, Richard et al. [9] reported that cognitively demanding auditory messages (that did not require the driver to respond verbally) could affect voluntary visual scanning, and the ability to detect changes in the traffic scene. Thus, there are reasons to investigate the relative potential in auditory messages to raise workload during driving.

In a collaboration project between Scania CV AB, Interactive Institute and Luleå University of Technology in Sweden, research addresses how audio design can meet the requirements of safe within-vehicle communication in heavy vehicles. The work presented in this article focus on the effectiveness of auditory signs to amplify traffic situation awareness (SA).

1.1 Auditory displays to support traffic SA

The importance of SA for safe driving has been described in the literature [10]. According to Endsley [11] SA is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'. Traffic SA can be seen as one component of the more general construct of SA. Cues that strengthen traffic SA may be regarding other road users and dangers, their position in relation to the own vehicle and how the situation is evolving over time.

One strategy to heighten awareness using auditory signals can be to direct visual attention to important events [12–14]. Fung et al. [12] demonstrated that an effective sound for a forward collision warning system was a simple tone of 2 kHz. The sound quickly made drivers pay attention to the road ahead and break fast. In a similar way, attention grabbing visual or tactile cues can be used to make the driver shift visual attention towards crucial information. In a recent study, Ho et al. [14] found that tactile cues may even be more effective than sound for this purpose.

But even though attention-grabbing signals are effective for some urgent events, there are reasons why to examine the use of more complex sound to convey traffic related information. First, many types of ITS such as night vision, blind spot detection and various road user protection systems are introduced in vehicles to assist in conditions and areas with low or no visibility. Other systems are developed to make drivers aware of accident-prone areas and potential dangers, such as intersections, bus stops and school areas. Information through sound can be an attractive means of communication in absence of fundamental visual information. Further, sounds that not only catch attention, but also carry the relevant information, may reduce the risk of visual overload in visually demanding traffic situations.

1.2 Auditory signs

A body of research has demonstrated how both verbal and nonverbal auditory signs can be used to convey information in user environments [15–18]. Evaluations of non-verbal signs have been partly focusing on advantages and disadvantages of sound types commonly referred to as earcons and auditory icons. The concept of earcons was first introduced by Blattner et al. [19], who defined them as 'non-verbal audio messages used in the user-computer interface to provide information to the user about some computer object, operation or interaction'. Blattner et al. suggested that earcons, like visual icons, could be divided into following classes: representational, abstract and semi-abstract. Gaver [20] investigated representational earcons, although he referred to them as auditory icons. Gaver defined auditory icons as 'everyday sounds mapped to computer events by analogy with everyday sound producing events'.

Ever since first introduced, earcons, auditory icons and other sound types such as spearcons [17] have been described and evaluated in research [21–26]. Brewster et al. [27] have done some important work evaluating earcons and suggesting design guidelines. They clearly focused on 'hierarchical earcons' and defined them as 'abstract, synthetic tones that can be used in structured combinations to represent parts of an interface'. Auditory icons have been described as an alternative to earcons in that they are nonmusical [17], real-life [22], natural and every-day sounds

[21].

At the International Conference for Auditory Display 2008, Mustonen [28] argued that the current definitions of non-verbal auditory signs are not compatible with the sign descriptions of, for example, semiotic science. He stated that ‘most signs we encounter are neither purely abstract nor iconic but combine both iconic and symbolic dimensions to make sense’. Further, he pointed out that the same sound could be listened to with different outcomes in different situations and orientations. ‘When listening to interface elements we intuitively recognise familiar parts from the sound and construct the meaning from their relation to the situation’.

Ulfvengren [18] investigated auditory warnings in aviation from a human error perspective. She argued that alerts should be meaningful in the context they are presented. These meaningful sounds are typically cues that exist naturally in the user environment, either as synthetic or non-synthetic sounds. One important aspect in warning design is to find signals that are easily associated to their assigned alert function meaning. Ulfvengren stated that ‘If a sound is possible to associate to a given alert function it requires fewer cognitive resources and is therefore appropriate, in this aspect, for auditory alert design’.

1.3 Auditory signs and traffic SA

McKeown [15] evaluated four sound types (auditory icons, environmental sounds, earcons and speech) to convey various types of in-vehicle information, including some traffic related information. Response time, accuracy of response, perceived urgency and scores of pleasantness were evaluated. The results clearly illustrated the potential in using sounds that have a meaning in the driving context. The environmental category of sounds consisted of real-world sounds that were likely to be familiar to drivers, but did not have any specific meaning within the vehicle interface. These sounds resulted in a degraded judgment performance compared to the more driving related sounds that McKeown categorised as auditory icons. It should, however, be pointed out that the response task used in the experiment was not accompanied by a concurrent driving task.

Vilimek and Hempel [21] investigated different sound types (auditory icons, earcons, keywords and long speech messages) to convey non-critical information in vehicles. Affects on short-term memory and choice reaction performance were collected. Earcons resulted in degraded response times compared to other sound types, while the long speech messages had a negative impact on serial recall. As in the study by McKeown, this experiment did not include a concurrent driving task. Also, the study focused on information related to vehicle functions, and no information about traffic events was included.

Chen, Qvint and Jarlengrip [29] evaluated the use of a 3D sound reproduction technique to improve traffic SA in a number of traffic situations. This study was conducted in a driving simulator and focused on driver acceptance. The authors concluded that auditory icons are suitable to this application due to their intuitiveness, distinguishability and relatively low degree of disturbance’.

Auditory icons seem to be more appropriate sounds to convey in-vehicle information than other sound types that has been evaluated in research, at least from a human information processing perspective. This is however not surprising. Mustonen [28], for example, wrote ‘the important difference of the earcon paradigm is that the design in auditory icon paradigm has been more focused on how the sound itself, through similarities and metaphors motivates the meaning creation process’. Auditory icons often sound like what they represent. This tends to make them meaningful to users in the specific context they are presented.

1.4 Objectives

Is context-specific meaning an important aspect to consider when designing auditory signals for traffic SA? The purpose of the study was to examine differences in learnability, cognitive demand and pleasantness for brief sounds that have a natural meaning in a driving context, and sounds that have been arbitrary mapped to traffic information. Prior to the experiment it was predicted that sounds that have a meaning in the driving context would be easier to learn compared to arbitrary sounds. The primary aim of the experiment was to investigate differences in cognitive effort after the drivers got a chance to learn the meaning of sounds. Differences in cognitive effort were estimated using a dual-task set-up, in which drivers responded to auditory signs while simultaneously performing a simulated driving task. Another aim of the study was to examine how the use of arbitrary sounds can impact driver satisfaction.

2 Method

2.1 Subjects

Eighteen truck drivers (17 males and 1 female) with self-reported normal hearing participated in the study. Their ages ranged between 22 and 61 (mean 39). Their truck driving experience ranged between 2 and 32 years (mean 16.8) and self-reported annual driving ranged between 2000 and 150 000 km (mean 75 410 km).

2.2 Apparatus

An illustration of the experimental setting is presented in Fig. 1. The experiment was conducted in a Scania R truck cab. A 10,4' touch monitor (Lilliput Electronics, CA, USA) showing videos of four hazardous traffic situations simultaneously during the driving sessions was positioned approximately on one arm length to the right of the driver. The video clips were brief .gif animations (1.26 s in length, continuously repeating), showing traffic situations from above.

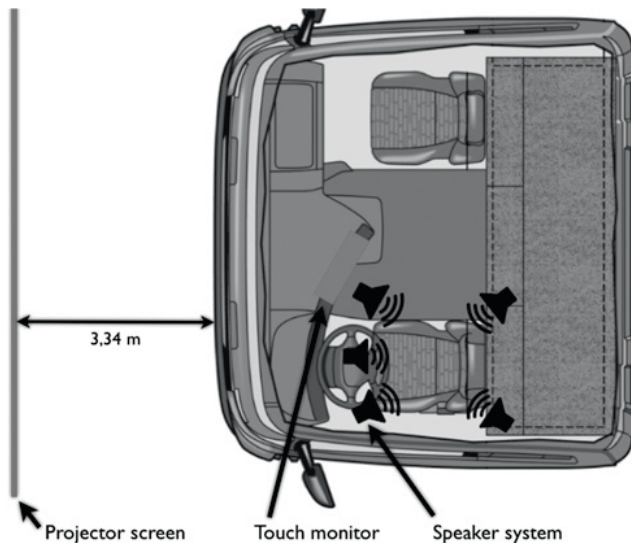


Figure 1 *Experimental set-up.*

A lane change test represented the driving task. The visual driving scene was projected using an Optoma EP 755 XGA DLP projector (Optoma Technology Inc., CA, USA) projecting an image 3.34 m in front of the cabin.

Presentation of auditory stimuli, traffic situations and the monitoring of driver responses were handled by a Java application running on a Lenovo Thinkpad T60 (Lenovo, NC, USA). Sound files were processed using a Kontakt 3 sampler (Native Instruments, Berlin, Germany) and an E-MU 1616m digital sound card (E-MU Systems Inc., CA, USA). The sounds were presented to participants at a comfortable listening level through an Anthony Gallo Nucleus Micro 5.1 channel speaker system (Anthony Gallo Acoustics Inc., CA, USA).

2.3 Dependent and independent variables

Two sets of non-verbal auditory signs were designed prior to the experiment. Each set contained five sounds mapped to road users (car, truck, pedestrian, children and bicycle). The first set of non-verbal auditory signs (arbitrary) consisted of five short musical motives. Brewster et al. [27] has suggested how musical timbre and rhythm can make sounds distinguishable from each other. Different rhythms and timbres were selected to make the sounds easy to tell apart. The second set of non-speech auditory signs (meaningful) consisted of sounds that are assumed to be meaningful to drivers. Road users make noise and they have their natural ways of catching the attention of other road users. These naturally occurring sounds should typically be meaningful to experienced drivers.

The final non-verbal signs are presented in Table 1. A set of speech messages was also designed and included in the experiment. A soft-spoken male voice was used for the verbal signs (verbal). Each speech message consisted of a keyword presented in Swedish describing the road danger. The different auditory signs were not exactly equal in length but ranged between 1 and 2 s. Spatial positions of road users were represented by presenting the sounds in the corresponding direction (front, rear, front-left, front-right, rear-left and rear-right). Combinations of road user types and positions resulted in a total number of 30 different traffic situations used in the study.

Table 1 Description of auditory signs used in the experiment.

	Meaningful	Arbitrary	Verbal
bicycle	bicycle bell	piano/G3-C3 – G3-C3	'bicycle'
car	horn	snare drum/roll	'car'
truck	truck horn	cello/C#2-D#2-F2-G#2 – C#2-D#2-F2-G#2	'truck'
pedestrian	man shout	marimba/D3-A3-A3-A3-A3-A3	'pedestrian'
children	children laugh	trumpet/G4-F#4-F4-E4-E4-E4	'children'

Learning time and trials, response time in judging traffic situations, accuracy of response (identity and position of road dangers) and subjective ratings of cognitive effort and pleasantness defined the dependent variables.

2.4 Procedure

The experiment was conducted using a within-subjects design. The participants were introduced to the simulator and the lane change test in a 5–10 min test drive. The experimenter also provided a short demonstration session explaining the judgment task. Subjects were told that they were evaluated on the basis of driving performance. They were required to judge the auditory signals as

fast as possible so that it would not affect the driving more than absolutely necessary. However, no parameters related to driving performance were actually monitored during the trials.

The trial consisted of three blocks, one for each condition, which lasted for about 30 min each. Every block started with a learning session, without the driving task, in which the participants were required to learn the intended mappings between sounds and road users. Images of the road users were presented on the touch screen and the driver were required to play the sounds until he/she felt comfortable with their meaning. Both learning time and trials were monitored.

The learning session was followed by the driving session. This part started with about 5 min of driving training without sounds. The driving task lasted for about 25 min. The auditory signs were presented in random order to the drivers with 20–60 s intervals. When a sound was played the drivers were required to select one out of four traffic situations presented on the touch screen. After each judgment the driver received feedback about their response. A green light indicated a correct response. A red light and text presenting the correct answer indicated an incorrect response. This feedback was built-in to allow drivers to learn from mistakes during the sessions. Directly after each driving session, the drivers rated the perceived cognitive effort and pleasantness using rating scales presented on the touch screen. These scales ranged from 1 (not at all challenging/annoying) to 10 (very challenging/annoying).

A loosely structured interview was conducted at the end of each trial in order to obtain complementary driver judgments. In this interview, the drivers were allowed to talk freely about any issues experienced during the trials. The experimenter especially paid attention to the participants' personal experiences regarding how they constructed meaning from the sounds.

3 Results

The statistical analysis of the data was performed using the computer package Minitab (Minitab Data Analysis Software, Philadelphia, PA, USA).

3.1 Learning

Average learning times and number of trials for the sign sets is presented in Table 2. As predicted, the drivers had serious problems learning the mappings between the arbitrary sounds and the traffic events. That is, the drivers listened to each sound 5.9 times compared to 1.93 times for the set of meaningful non-verbal signs and 1.52 times for the verbal signs. A one-way analysis of variance (ANOVA) revealed significant differences in learning time $F(2, 34) = 21.03$, $p < 0.01$ and trials $F(2, 34) = 28.22$, $p < 0.01$. Post-hoc analyses were conducted using Tukey's honestly significantly different (HSD) test. Both learning time and trials were significantly higher in the arbitrary condition than the two other conditions ($p = 0.01$).

Table 2 Mean learning time and number of trials.

	Time in seconds (SD)	Trials (SD)
meaningful	24.7 (8.7)	9.6 (2.9)
arbitrary	90.2 (59.6)	29.5 (16.4)
verbal	23.3 (12.4)	7.6 (3.3)

3.2 Cognitive effort

Table 3 shows response times and response accuracy for the three conditions and Table 4 presents response times, accuracy of responses in terms of identity of road dangers and position of road dangers. The drivers judged 30 traffic situations in each session. The arbitrary sounds resulted in longer response times and degraded response accuracy compared to the other two conditions. A one-way ANOVA revealed significant differences in response time $F(2, 34) = 27.56$, $p < 0.01$ and accuracy $F(2, 34) = 56.19$, $p < 0.01$. A Tukey's HSD test showed a significant difference between the arbitrary condition and the two other conditions ($p = 0.01$). Significant effects were also found both in terms of identification of road dangers $F(2, 34) = 69.99$, $p < 0.01$ and position of road dangers $F(2, 34) = 16.77$, $p < 0.05$. A Tukey's HSD test found that the arbitrary sounds resulted in more errors both in terms of identity and position of road dangers ($p = 0.01$).

Table 3 Mean response time and accuracy of response.

	Time in seconds (SD)	Error % (SD)
meaningful	3.00 (0.67)	13.7 (10.5)
arbitrary	4.12 (1.30)	33.0 (14.6)
verbal	3.11 (0.62)	12.2 (9.0)

Table 4 Mean accuracy of response in terms of identity and position of road users.

	Identity % (SD)	Position % (SD)
meaningful	2.4 (5.6)	12.8 (9.8)
arbitrary	26.7 (12.2)	23.9 (15.0)
verbal	2.6 (5.8)	10.9 (7.8)

3.3 Subjective ratings

The subjective ratings of pleasantness and cognitive effort are presented in Table 5. The arbitrary sounds were rated more annoying and more challenging to interpret while simultaneously performing the driving task compared to the other two sound sets. A significant effect was found for interpretation $F(2, 34) = 15.32$, $p < 0.01$ and annoyance $F(2, 34) = 7.47$, $p < 0.01$. The post-hoc analysis reported significant effects between the arbitrary sounds and the other conditions ($p = 0.01$).

Table 5 Mean subjective ratings of pleasantness and cognitive effort.

	Pleasantness (SD)	Cognitive effort (SD)
meaningful	3.45 (2.09)	5.61 (1.97)
arbitrary	5.39 (2.83)	7.39 (1.78)
verbal	3.56 (1.76)	5.50 (2.15)

4 Discussion

The purpose of the study was to evaluate learnability, cognitive demand and pleasantness of auditory signs designed to support drivers' traffic SA. Sounds assumed to have a natural meaning in the driving context were compared with arbitrary sounds and verbal signs. In the interview carried out at the end of each trial, a majority of the drivers reported that they tried to make the arbitrary sounds meaningful by finding intuitive similarities and forming associations between the signs and the road users. For instance, one subject stated, 'the musical motive representing the big truck was the easiest one to recognise since the cello is playing in a low register'. This association definitely makes sense. Large objects vibrate more slowly than small objects and thus produce lower tones. An instrument playing in a low register could therefore signify a large object moving. Another driver said that he tried hard to establish an association between the sound of a trumpet and a child playing the trumpet. However, most drivers reported that they failed to establish durable and useful associations between the arbitrary sounds and the traffic events. Even though they spent considerable more time and trials trying to learn the meaning of the sounds, their judgment performance was degraded in this condition compared to the other two conditions. Significant effects were found both in terms of response time and accuracy of response. In fact, none of the 18 truck drivers performed better when interpreting the arbitrary sounds compared to the other two conditions.

Taken together, the results of the experiment support the hypothesis that sounds that are meaningful in the driving context require considerable less cognitive resources compared to sounds arbitrarily mapped to traffic information. This effect was found even though drivers spent more time and trials learning the arbitrary sounds. The lack of meaning was apparently not compensated by the longer learning sessions. Many sounds we encounter in user environments are arbitrary and meaningless sounds. The results of this study emphasise the use of sounds that have a natural meaning in the driving context and are easily associated with their intended meaning. The study also demonstrates that brief sounds imitating road users may be appropriate when designing especially for traffic SA.

During the trials the drivers were required to respond to the sounds as fast as possible so that it would not affect driving performance more than absolutely necessary. The drivers were told they were judged primarily on the basis of their driving performance. But sometimes the arbitrary sounds resulted in exceptionally long response times (10–15 s). This happened for three subjects (17%) and represented 1.5% of the measurements. In these situations, the drivers were not able to find a solution within a reasonable timeframe. Despite the time pressure, they remained motionless staring at the touch screen for long periods, completely losing focus on the road. It seems like the arbitrary sounds contributed to a severe level of attentional narrowing or even cognitive overload for some drivers. It can be argued that the attentional narrowing was intensified by stress induced by the time pressure [30]. The behaviour was very inappropriate since the drivers were not able to focus visually on the screen and on the road scene simultaneously. In a real driving situation, longer periods of attentional narrowing induced by interface elements could significantly impact on drivers' ability to perceive and process other driving-related information.

The drivers performed equally fast and accurate when interpreting meaningful non-verbal signs as they did when interpreting short verbal signs. This motivates a more extensive comparison between these two types of sounds. They both have potential advantages and disadvantages. Speech is known to be sensitive to other verbal communication or background noise. However, a modern truck cab is a relatively controlled sound environment. Some newer models can even mute sounds (radio, telephone signals, etc.) that are not considered appropriate in the particular situation. Vilimek and Hempel [21] found that long verbal messages (>3.5 s) could have a negative impact on short-term memory. But if keywords can be used, verbal messages seems promising. A strong

argument to develop non-verbal signs is the potential to find more universal signs that are not language dependent. Also, recent research on verbal communication has promoted the importance of voice adaption when designing for in-vehicle systems [31]. Voice familiarity, gender, age and emotional tone may have considerable impact on both system driver attitude and driving performance. No particular type of voice seems to fit all drivers, which in turn can make development of speech-based displays challenging.

One general issue with meaningful non-verbal sounds is that they can be hard to find. Some objects in a traffic scene do not even produce sound. Producing comprehensible speech-based messages may be easier.

A general issue in audio interface design is how to find sounds that will not be annoying. Annoyance may be a desirable quality in some very urgent situations. In other words, in most everyday situations, it is important to find signals that are pleasant to listen to. In the present study, the participants rated perceived annoyance at the end of each experimental condition. That is, the driver rated the arbitrary assigned sounds more annoying than the more meaningful sounds. The results give us some indication of how arbitrary sounds implemented in vehicles can have a negative impact on user satisfaction. McKeown [15] also reported low scores of pleasantness for abstract sounds compared to other verbal and non-verbal signs.

One potential criticism of the study is that the laboratory set-up is not really comparable to realistic driving. The lane change test requires the driver to focus on the forward road scene. However, it does not fully represent the dynamic task of driving. Also, in the study the drivers' interpreted 90 auditory signs in about 1 h of driving. This high frequency of sounds would have promoted a higher attentiveness than is typical in routine driving.

5 Future work

The concept of using sound as a primary channel for traffic-related information need to be further evaluated. Future experiments should examine driver's behaviour and effects on driving that can be directly related to safety. Also, previous work has shown how complexity of the traffic environment can significantly affect workload, both for experienced and inexperienced drivers [32]. Future evaluations should address the efficiency of auditory signs in traffic situations with different levels of complexity. Finally, we still know little about how auditory displays using auditory signs can disturb and confuse drivers during real driving. Thus, it would be very interesting to validate the result of the present study in a real-world setting. Such a study would give us a better understanding of how informative auditory displays may support and confuse experienced drivers during real driving.

6 Acknowledgments

Scania CV AB and The Swedish Governmental Agency for Innovation Systems (Vinnova) financed this work. A special thanks to Stefan Lindberg at the Interactive Institute for helping us with the sound design, and to Robert Friberg and Josefin Nilsson at Scania CV AB for support and inspiration.

7 References

- [1] KIRCHER A., LINDER A., NYGÅRDHS S., VADEBY A.: 'Intelligenta transportsystem, ITS, i passagerarbilar och metoder för utvärdering av dess inverkan på trafiksäkerheten' (Swedish National Road and Transport Research Institute, Linköping, Sweden, December 2007, 1st edn.)
- [2] ALM H., NILSSON L.: 'The effects of a mobile telephone task on driver behavior in a car following situation', *Accident Anal. Prev.*, 1995, 27, (5), pp. 707–715
- [3] ENGSTRÖM J., JOHANSSON E., ÖSTLUND J.: 'Effects of visual and cognitive load in simulated motorway driving', *Transp. Res. Part F*, 2005, 8, (2), pp. 97–120
- [4] STRAYER D.L., DREWS F.A.: 'Cell-phone-induced driver distraction', *Curr. Dir. Psychol. Sci.*, 2007, 16, (3), pp. 128–131
- [5] NEALE V.L., DINGUS T.A., KLAUER S.G., SUDWEEKS J., GOODMAN M.: 'An overview of the 100-car naturalistic study and findings'. National Highway Traffic Safety Administration, Washington, DC, USA, 2005, Paper No. 05-400
- [6] RECARTE M.A., NUNES L.M.: 'Effects of verbal and spatial imagery task on eye fixations while driving', *J. Exp. Psychol. Appl.*, 2000, 6, (1), pp. 31–43
- [7] PATTEN C., KIRCHER A., ÖSTLUND J., NILSSON L.: 'Using mobile phones: cognitive workload and attention resource allocation', *Accident Anal. Prev.*, 2004, 36, (3), pp. 341–350
- [8] MCCARLEY J.S., VAIS M.J., PRINGLE H., KRAMER A.F., IRWIN D.E., STRAYER D.L.: 'Conversation disrupts change detection in complex traffic scenes', *Hum. Factors*, 2004, 46, (3), pp. 424–436
- [9] RICHARD C.M., WRIGHT R.D., Ee C., Prime S.L., Shimizu Y., Vavrik J.: 'Effect of a concurrent auditory task on visual search performance in a driving-related image-flicker task', *Hum. Factors*, 2002, 44, (1), pp. 108–119
- [10] KASS S.J., COLE K., LEGAN S.: 'The role of situation awareness in accident prevention' in DE SMET A. (ED.): 'Transportation accident analysis and prevention,' (Nova Science Publishers, Inc., 2008, 1st edn.), pp. 107–122
- [11] ENDSLEY M.R.: 'Design and evaluation for situation awareness enhancement'. Proc. Human Factors Society 32nd Annual Meeting, Santa Monica, USA, 1988
- [12] FUNG C.P., CHANG S.H., HWANG J.R., HSU C.C., CHOU W.J., CHANG K.K.: 'The study on the influence of auditory warning systems on driving performance using a driving simulator'. Institute of Transportation, Taiwan, 2007, Paper no. 07-0170
- [13] HO C., SPENCE C.: 'Assessing the effectiveness of various auditory cues in capturing a driver's visual attention', *J. Exp. Psychol. Appl.*, 2005, 11, (3), pp. 157–174
- [14] HO C., SPENCE C., TAN H.Z.: 'Warning signals go multisensory'. Proc. HCI Int. 2005, Las Vegas, USA, 2005
- [15] MCKEOWN D.: 'Candidates for within-vehicle auditory displays'. Proc. Int. Conf. Auditory

Display, Limerick, Ireland, 2005

[16] GAVER W.W.: 'The SonicFinder, a prototype interface that uses auditory icons', *Hum. Comput. Interact.*, 1989, 1, pp. 67–94

[17] WALKER B.N., NANCE A., LINDSAY J.: 'Spearcons: speech based earcons improve navigation performance in auditory menus'. *Proc. Int. Conf. Auditory Display*, London, UK, 2006

[18] ULFVENGREN P.: 'Design of natural warning sounds'. *Proc. Int. Conf. Auditory Display*, Montreal, Canada, 2007

[19] BLATTNER M., SUMIKAWA D., GREENBERG R.: 'Earcons and icons: their structure and common design principles', *Hum. Comput. Interact.*, 1989, 4, (1), pp. 11–44

[20] GAVER W.W.: 'Auditory icons: using sound in computer interfaces', *Hum. Comput. Interact.*, 1986, 2, (2), pp. 167–177

[21] VILIMEK R., HEMPEL T.: 'Effects of speech and non-speech sounds on short-term memory'. *Proc. Int. Conf. Auditory Display*, Limerick, Ireland, 2005

[22] BUSSEMAKERS M.P., DE HAAN A.: 'When it sounds like a duck and looks like a dog. Auditory icons vs. earcons in multimedia environments'. *Proc. Int. Conf. Auditory Display*, Atlanta, USA, 2000

[23] DINGLER T., LINDSAY J., WALKER B.: 'Learnability of sound cues for environmental features: auditory icons, earcons, spearcons and speech'. *Proc. Int. Conf. Auditory Display*, Paris, France, 2008

[24] LEUNG Y.K., SMITH S., PARKER S., MARTIN R.: 'Learning and retention of auditory warnings'. *Proc. Int. Conf. Auditory Display*, Paolo Alto, USA, 1997

[25] LEMMENS P.M.C., BUSSEMAKERS M.P., DE HAAN A.: 'Effects of auditory icons and earcons on visual categorization: the bigger picture'. *Proc. Int. Conf. Auditory Display*, Espoo, Finland, 2001

[26] STEPHAN K.L., SMITH S.E., PARKER S.P.A., MARTIN R.L., MCANALLY K.I.: 'Auditory warnings in the cockpit: an evaluation of potential sound types'. *Innovation and consolidation in aviation: selected contributions to the Australian Aviation Psychology Symp.* 2000, 2003

[27] BREWSTER S., WRIGHT P., EDWARDS A.: 'A detailed investigation into the effectiveness of earcons'. *Proc. Int. Conf. Auditory Display*, Santa Fe, USA, 1992

[28] MUSTONEN M.S.: 'A review-based conceptual analysis of auditory signs and their design'. *Proc. Int. Conf. Auditory Display*, Paris, France, 2008

[29] CHEN F., QVINT, G., JARLENGRIP J.: 'Listen! there are other road users close to you – improve the traffic awareness of truck drivers,' in STEPHANIDIS C. (ED.): 'Universal access in human computer interaction, ambient interaction' (Springer, 2007, 1st edn.), pp. 323–329

[30] KOWALSKI-TRAKOFLER K.M., SCHARF T., VAUGHT C.: 'Judgement and decision making under stress: an overview for emergency managers', *Emer. Manage.*, 2003, 1, (3), pp. 278–289

[31] JONSSON I.M.: 'Social and emotional characteristics of speech-based in-vehicle information systems: impact on attitude and driving behaviour'. PhD thesis, Linköping University, 2009

[32] PATTEN C., KIRCHER A., ÖSTLUND J., NILSSON L., SVENSON O.: 'Driver experience and cognitive workload in different traffic environments', *Accident Anal. Prev.*, 2006, 38, (5), pp. 887–894

PAPER 2

Fagerlön, J. (in press). Urgent alarms in trucks, effects on annoyance and subsequent driving performance. *IET Intelligent Transport Systems*.

This paper is a preprint of a paper accepted by IET Intelligent Transport Systems and is subject to Institution of Engineering and Technology Copyright. When the final version is published, the copy of record will be available at IET Digital Library.

Urgent alarms in trucks: effects on annoyance and subsequent driving performance

Johan Fagerlönn

Interactive Institute - Sonic Studio, SE-94128, Piteå, Sweden, johanf@tii.se.

Abstract: Previous research has shown that urgent auditory warnings are likely to annoy drivers. Increased urgency could also raise drivers' stress levels, which in turn could impact their ability to detect and react to subsequent changes in the traffic environment. We conducted a simulator experiment with 24 truck drivers to investigate the potential of urgent alarms to raise annoyance and negatively affect drivers' subsequent responses to unrelated, critical events on the road. The drivers received two types of warnings that were designed to significantly differ in perceived urgency. Several times in the trial, a critical event occurred just seconds after drivers were presented with an unrelated warning, and the drivers had to brake immediately to avoid a collision. The results indicate that acoustic characteristics and semantic meaning may impact the perceived annoyance of in-vehicle warnings. Interestingly, we found a significant, negative correlation between the drivers' experience (years of truck driving experience) and the rated annoyance for both types of warnings. Also, the drivers who received the high-urgency warning braked significantly harder and tended to brake later than the drivers who received a low-urgency warning. These results have implications for ITS systems for heavy vehicles that intend to make use of auditory warning signals.

1 Introduction

According to a recently published study, about 100 persons are killed every year in Sweden as a result of accidents involving heavy goods vehicles. This statistic represents approximately 20 percent of all persons killed in road accidents in the country [1]. The high risk of being seriously injured or killed in accidents involving heavy vehicles provides the motivation for researchers to examine the causes behind these accidents and to find safe, satisfactory solutions.

Auditory signals may be especially useful in critical driving situations because sound has unique advantages for events that require rapid responses. Human hearing is omnidirectional and cannot be shut off involuntarily, whereas visual warnings must be seen in order to be effective [2]. Previous ITS research has demonstrated the potential for sounds to alert drivers and improve safety. Ho and Spence [3], for instance, investigated the effectiveness of spatially predictive and non-predictive auditory cues to catch drivers' attention in a simulated driving task. The participants responded to urgent situations by braking or accelerating. A rapid serial visual presentation (RSVP) task was used to distract the drivers. The results showed that a spatially predictive signal (car horn sound or verbal message) effectively led to fast responses. Fung et al. [4] used an advanced driving simulator to examine the usefulness of auditory cues for a collision avoidance system. The study revealed that a very simple auditory signal (2 kHz tone) made distracted drivers shift their attention to the road and brake rapidly.

The number of auditory warnings and alerts increases with the number of in-vehicle systems. To find optimal auditory solutions, we need to learn more about the negative consequences of auditory warnings on drivers. The present study focused on commercial truck drivers and the ways that

persistent auditory warnings can raise annoyance levels and negatively affect drivers' performance in commercial vehicles.

1.1 Perceived urgency

Auditory alarms differ from other salient sounds in a working environment because they are specifically designed to indicate urgency and danger. In warning design, it is crucial for the warning's urgency to correspond to the urgency of the situation [5]. Appropriate "urgency mapping" could help a system user to understand the warning and respond more effectively. More urgent sounds can lead to faster responses, at least when the response task is simple [6-8]. Research in the driving domain has reported that such sounds can speed up drivers' accelerator release in urgent situations [9]. However, urgency mismatching can undermine a warning's effectiveness. For instance, if a driver perceives a collision warning as less urgent than a signal for vehicle failure or an incoming e-mail, she or he is likely to be confused.

What makes an auditory warning sound urgent? Previous research has shown that urgency can be systematically manipulated by the modulation of fundamental acoustic properties such as loudness, pitch, speed and amplitude envelope shape [6, 10, 11] (see [12] for a recent review of the literature and design recommendations for crash warning interfaces). Rated urgency also depends on the listeners' "mental representation" of the warning's cause [13], and these mappings could override acoustic characteristics. Burt et al. [14], for instance, reported that participants could rank sounds based on acoustic parameters before an experiment in which the warnings were mapped to specific situations but were unable to do so after the experiment. Wiese and Lee [9] investigated e-mail alerts and collision warnings for in-vehicle use and found that, in both cases, acoustic parameters had no significant effect on urgency ratings, although drivers rated collision warnings as more urgent than e-mail alerts.

1.2 Annoyance of sound

A general goal in auditory signal design is to create sounds that will not annoy users. Sound annoyance can be defined as "an evaluative response towards the sound and its source, including both emotional ('nuisance', 'unpleasantness') and cognitive aspects ('disturbance', 'interference')" [15]. Annoyance is an important consideration for warning design because it could cause users to reject the system. Block, Nuutinen and Ballast [16] reported that unpleasant signals in the operating room are a common reason for users to turn off auditory alarms. Research on sound annoyance has largely focused on the effects of environmental noise. It has been suggested that annoyance may be predicted with acoustic or psychoacoustic metrics. For example, Khan et al. [17] found that loudness, sharpness and harmonic ratio can predict drivers' annoyance with diesel engine noise. However, annoyance depends on semantic and contextual factors. For instance, although loud sounds are annoying in some situations, people at a rock concert might find loud music more satisfying [18]. Ellermeier et al. [19] studied annoyance with identifiable and neutralised everyday sounds. They concluded that psychoacoustic metrics could be used to predict annoyance of neutralised sounds but that the annoyance ratings may differ when sounds are identifiable. Sound interference with ongoing mental tasks is another factor that may raise annoyance levels [15].

1.3 Annoyance and in-vehicle warnings

Sound annoyance cannot be predicted by acoustic and psychoacoustic properties alone, and therefore, we stress the importance of studying drivers' annoyance with warning signals in realistic settings. To date, few studies have focused on both the urgency and annoyance of warnings in vehicles. Tan and Lerner [20] evaluated the alerts for a collision warning system and reported that

ratings of loudness correlated with ratings of urgency ($r=0.93$) and annoyance ($r=0.86$). Wiese and Lee [9] reported that warnings designed to sound urgent tended to speed up drivers' accelerator release but that drivers also rated them as more annoying. Marshall et al. [21] examined the effects of range for acoustical parameters (harmonic series, pulse duration, inter-pulse interval, alert onset and offset, burst duty cycle, inter-burst period and sound type) in nonverbal auditory warnings and found that all of the parameters affected both perceived urgency and annoyance. This investigation was not, however, conducted in a real or simulated driving setting. Instead, the participants read brief descriptions of the driving scenarios and imagined hearing the alerts from the in-vehicle systems. In conclusion, previous research has suggested that the acoustical parameters that affect urgency can also increase annoyance. However, drivers' annoyance with in-vehicle warnings has also been shown to depend on semantic factors. McKeown [22] reported that drivers consistently rate sounds mapped to more urgent driving situations as less pleasant.

1.4 Perceived urgency and stress

There is reason to believe that urgent warnings can negatively impact driving performance and safety. In a simulator study, Graham [23] found that auditory icons sometimes induced inappropriate responses to false alarms. He suggested that the high level of urgency these sounds convey prevents participants from taking enough time to assess the road situation for themselves. Baldwin [24] examined the semantic and acoustical properties of verbal warning signals and reported that signals of intermediate urgency decreased crash risk during simulated driving; however, the high-urgency warning used in the experiment did not reduce crash risk. We define high urgency in the present context as a situation requiring immediate action or attention [8]. Perceived urgency represents an increased level of threat or a sense of time pressure that can provoke stress-induced arousal. Ratings of perceived urgency have been reported to correspond to ratings of emotional activation [25]. An established effect of stress and high arousal levels is attentional narrowing [26, 27]; in other words, the individual's focus of attention shrinks, and he or she focuses on critical issues and elements [28]. Chapman and Underwood [29] investigated the visual behaviour of drivers while they observed driving situations with different levels of danger and found that more dangerous (arousing) situations were "characterised by a narrowing of visual search, shown by an increase in fixation duration, a decrease in saccade angular distances, and a reduction in the variance of fixation locations".

1.5 Objectives

Previous research has indicated that acoustical parameters that affect warning urgency could raise annoyance, and potentially also negatively affect the listener's ability to respond to visual information. However, it is uncertain how these previous findings will apply in commercial drivers performing a driving task. We conducted the present study to test the following two hypotheses.

1. Warning signals with a higher level of psychoacoustic urgency (conveyed by acoustic parameters) will be perceived as more annoying by commercial truck drivers.
2. Warnings that express higher levels of psychoacoustic urgency have a negative effect on truck drivers' ability to detect and respond to a subsequent, unpredictable change on the road ahead.

A warning signal's loudness is related to perceived urgency [6, 7]. However, very loud signals are known to produce severe startle responses. Therefore, we decided to examine signals at reasonable and realistic intensity levels. Volume settings for the signals used in the experiment were based on the subjective judgements of the experimenters.

2. Methodology

2.1 Participants

A total of 24 professional truck drivers (3 female) between the ages of 23 and 70 years ($M=43.3$, $SD=13.1$) participated in the study. Their years of truck driving experience ranged from 1 to 46 years ($M=20.9$, $SD=12.9$). The drivers reported an annual driving distance of between 15,000 and 150,000 km ($M=90218$, $SD=3838$). The participants' hearing was not tested. However, none of the drivers reported any significant hearing disorders.

2.2 Apparatus

The experiment was conducted in a simulator at the Swedish National Road and Transport Research Institute. The "VTI Driving Simulator III" has a motion system and a vibration table that can simulate acceleration forces and a variety of road conditions. The virtual traffic scene is projected onto three screens covering 120 degrees of the visual field. To make the driving task as natural as possible, we did not provide headphones for the auditory stimulus. Instead, a 6.0 speaker setup (Anthony Gallo Acoustics Inc., CA, USA) was installed in the truck cab prior to the experiment.

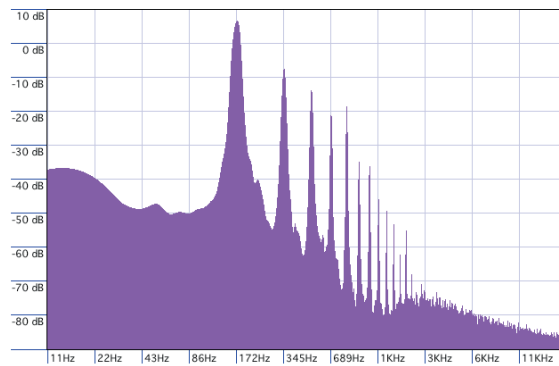


Figure 1 Frequency characteristics for the pulses in the low-urgency warning.

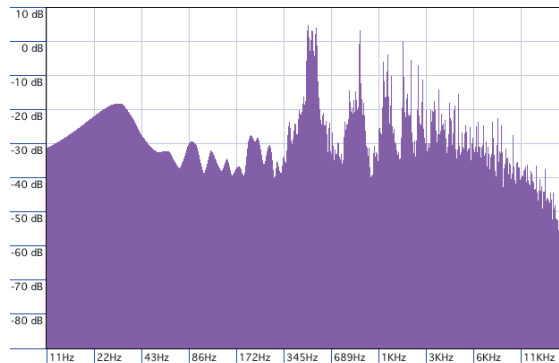


Figure 2 Frequency characteristics for the pulses in the high-urgency warning.

2.3 Design of stimulus

The experiment included two auditory warning signals that were both designed to warn drivers about pedestrians standing close to the roadside. The warnings started with a brief, 300-ms verbal message, “pedestrians”, which was presented in Swedish by a female voice. The message was followed by one of two 1500-ms tone bursts that were designed to differ significantly in urgency. A warning signal’s speed has been reported to affect its perceived urgency [7, 10, 21]. The low-urgency warning consisted of 2 pulses with a 300-ms inter-pulse interval. The high-urgency sound consisted of 8 pulses, which were played in a constant tempo with 10-ms inter-pulse intervals. High-pitched signals have been reported to amplify urgency [6, 10, 11]. The low-urgency warning had a base frequency of 179 Hz (G3). The high-urgency warning consisted of a cluster of tones with the following base frequencies: 491 Hz (B4), 522 Hz (C5), 554 Hz (C#5), 1046 Hz (C6) and 1974 Hz (B6). Figures 1 and 2 present the frequency characteristics for the pulses in the high-urgency and low-urgency warnings. Shorter amplitude onset and offset have been reported to increase urgency [10, 21]. The amplitude onset and offset times for the low-urgency warning were 300 ms and 450 ms, and the onset and offset times for the high-urgency warning were 25 ms and 210 ms. Haas et al. [6] and Haas et al. [7] reported that higher signal levels increased urgency. The signal levels (sound pressure levels on the dBA scale, maximum values, measured near the position of the drivers’ head) for the warnings were calibrated to approximately 80 dBA for the low-urgency warning and 85 dBA for the high-urgency warning. A-weighting of sound pressure levels (dBA) is widely used to adjust sound measurements to correspond to loudness as perceived by the listener. The signal levels were held constant throughout the trials. The background engine noise was calibrated to approximately 64 dBA at the drivers’ position at 50 km/h speed to make the auditory warnings clearly audible without being unrealistically loud or startling.

2.4 Stimulus evaluation

A stimulus evaluation was conducted before the main experiment to investigate the potential of the warnings to cause alarm or annoyance. A sample of 18 subjects (16 males and 2 females), none of whom participated in the main experiment, took part in the evaluation. Their ages ranged from 20 to 56 years ($M=32.4$, $SD=8.4$), and the experiment was conducted in an open office environment. The participants listened to the warnings at a comfortable volume level through Koss UR5 headphones (Koss Corporation, WI, USA). The warning signals were presented in counterbalanced order, and the participants rated the sound for both annoyance and “perceived alarming response” using 7-point scales ranging from “not at all” to “very much”. The results are presented in table 1. The two warnings had a consistent effect on both perceived alarm and perceived annoyance. Paired Students t-tests were used to test for significance between distributions. 17 of the 18 subjects rated the low-urgency warnings as less alarming, and all the subjects rated the low-urgency warning as less annoying than the high-urgency warning.

Table 1 Ratings of alarm and perceived annoyance in the stimulus evaluation conducted before the main experiment.

	High urgency (SD)	Low urgency (SD)	p-value
Alarming, 1-7	4.6 (2.0)	2.6 (1.7)	<0.01
Annoying, 1-7	5.5 (1.2)	3.0 (1.8)	<0.01

2.5 Critical situations

In the critical situations, a bus that was parked at a bus stop suddenly started to pull out in front of the truck (see figure 3). This situation forced the drivers to brake immediately to avoid a collision. In total, the critical event occurred 3 times: once after a high-urgency warning, once after a low-urgency warning and once without any warning. The two auditory warnings concerned pedestrians standing in a formation about 2 meters from the roadside and approximately 20 meters from the bus. The pedestrians stood in a small formation and seemed to be interacting with each other. The pedestrians did not move, and there was no reason for the drivers to brake for them.



Figure 3 *Traffic situation with pedestrians and a parked bus. The drivers received a warning about the pedestrians standing to the right. Moments later, the bus pulled out in front of the truck.*

2.6 Design and procedure

We used a within subjects-design, in which all the drivers received both types of warnings. The order of warnings was counterbalanced to minimise order effects. The drivers received written information about the study upon arrival. They also gave their written consent and provided demographic information. The drivers were told that they were participating in a test of an in-vehicle warning system designed to warn them about potential dangers in the traffic environment. However, they were not informed of the study's specific aim at that point. The participants started with a practice driving scenario that lasted approximately 8 minutes that gave the drivers a chance to ask the experimenter questions and familiarise themselves with the simulator. The main driving task lasted for 25-30 minutes. The drivers were told to drive normally and not to exceed the speed limits. The traffic environment consisted of a mix of rural and urban roads. In total, every driver passed 18 buses during a trial. After a critical event (a bus pulled out in front of the truck), the drivers followed the bus for about a minute until the next bus stop. The participants were not instructed what to do in response to the warnings. They received both the high-urgency and low-urgency warning a number of times in each trial (one low-urgency warning in the practice scenario), in addition to the signals presented prior to the unrelated critical events. Also, a few times in each trial another critical event occurred (a car suddenly appeared from the right in an intersection), sometimes with a preceding unrelated warning. However, the system did not give any other types of warnings, only those in response to pedestrians. After the driving task, the participants completed a questionnaire that investigated how they perceived the sounds and whether they expected the critical situations. After completing the questionnaire, we revealed the specific

research questions, and the drivers were able to ask any questions about the study and the research project.

2.7 Dependent measures

The critical situations were designed so that the drivers had to brake to avoid a collision. Participant brake response time and response force were therefore the main dependent variables. We defined brake response time as the time that elapsed between the bus starting to pull out and the driver starting to brake. We defined brake response force as the brake pressure level measured by the simulator's brake system. The driving parameters were sampled at 50 Hz. In the post-trial questionnaire, the subjects rated annoyance and perceived alarm for both sounds using rating scales ranging from 1 (not at all) to 7 (very much).

3 Results

3.1 Subjective ratings

Table 2 shows the mean values for the subjective ratings. A total of 13 drivers (54%) rated the high-urgency signal as more annoying than the low-urgency sound. A two-tailed, paired t-test revealed that the difference between the distributions was significant ($t(23)=2.94$, $p=0.007$). Furthermore, 9 drivers rated both warnings as equally annoying, and 2 drivers rated the low-urgency warning as more annoying. The drivers who rated the high-urgency warning as equally or less annoying than the low-urgency sound tended to give the more urgent warning a low score ($M=3.0$, $SD=1.66$). A total of 12 drivers (50%) rated the high-urgency warning as more alarming. The difference between the conditions was significant ($t(23)=3.14$, $p=0.005$, two-tailed). Only one driver rated the low-urgency sound as more alarming. Similar to the annoyance ratings, the drivers who considered the high-urgency sound equally or less annoying than the low-urgency sound tended to give the warnings low scores ($M=2.69$, $SD=1.70$). The correlation between the ratings of annoyance and "perceived alarm response" was significant for both the high-urgency warning ($r=0.60$, $p<0.05$, two-tailed) and the low-urgency warning ($r=0.57$, $p<0.05$, two-tailed).

Table 2 Subjective ratings of annoyance and perceived alarm

	High urgency (SD)	Low urgency (SD)
Annoying, 1-7	4.42 (1.84)	3.42(1.56)
Alarming, 1-7	3.71(1.88)	2.71 (1.60)

We also calculated correlations between demographic variables (age and years of driving experience) and subjective ratings. Interestingly, we found significant negative correlations between "years of experience" and the rated annoyance for both the high-urgency warning ($r=-0.41$, $p<0.05$, two-tailed) and the low-urgency warning ($r=-0.43$, $p<0.05$, two-tailed). The relationship between the drivers' age and annoyance rating was slightly weaker and was not significant for either warning ($r=-0.31$, -0.24 , $p=ns$). We found no considerable correlations between the other variables.

3.2 Brake response

All of the drivers braked for the bus and avoided a collision in the critical situations. In addition, none of the drivers made any inappropriate direct responses to the warnings, such as braking hard. Such behaviour would have been inappropriate since the pedestrians were standing still, relatively far away from the roadside. Table 3 shows the results for brake performance. Two-tailed, paired t-tests failed to show significant effects for any of the dependent variables.

Table 3 Brake response time and brake force.

	High-urgency (SD)	Low-urgency (SD)
Response time in ms	1441 (381)	1352 (284)
Brake pressure in bar	4.50 (2.33)	3.76 (1.79)

Brake responses in first situations

The drivers responded more slowly in the first critical situation ($M=1559$ ms, $SD=320$ ms) than in the second critical situation ($M=1233$ ms, $SD=269$ ms). A two-tailed, paired t-test showed that the difference was significant ($t(23)=3.63$, $p=0.001$, two-tailed). In addition, the drivers rated the last critical situation as considerably more expected ($M=5.33$, $SD=1.40$) than the first critical situation ($M=3.46$, $SD=1.93$). We therefore decided to examine the results from the first situations in more detail. The mean time between the driver receiving a warning and the bus pulling out in the first situation was 2564 ms ($SD=769$).

Table 4 presents the mean brake response times and brake force for the first critical situation. The drivers who received an urgent warning tended to brake more slowly ($M=1637$ ms, $SD=370$ ms) than the drivers who received a low-urgency warning ($M=1482$ ms, $SD=251$ ms), but the difference was not statistically significant ($t(22)=1.20$, $p=0.24$, two-tailed). The drivers who received an urgent warning braked harder than the drivers who received a low-urgency warning. We did not assume a normal distribution of data. A two-tailed, Mann-Whitney U-test and a two-tailed, independent samples t-test showed that the difference was significant ($U=113$, $n_1=n_2=12$, $p<0.05$), ($t(22)=2.43$, $p<0.05$, two-tailed). The correlation between the response time and brake force was significant ($r=0.52$, $p<0.01$, two-tailed).

Table 4 Brake response time and brake force in the first critical situation.

	High-urgency (SD)	Low-urgency (SD)
Response time in ms	1637 (370)	1482 (251)
Brake pressure in bar	6.06 (2.05)	4.23 (1.74)

4 Discussion

4.1 Annoyance

Many of the drivers found the high-urgency warning considerably more annoying than the low-urgency warning. This finding supports previous findings that the alert parameters that amplify warning signal urgency also increase annoyance. Our results emphasise that the design of non-speech auditory warnings for commercial vehicles should take into account both annoyance and urgency. A sound's annoying potential is especially important for the design of low-urgency and everyday situations or situations with a high risk of false and nuisance alarms. Block et al. [16], for instance, reported that false alarms are the most common reason for operators turning off the volume on technical systems. Signals that are perceived as unpleasant are likely to become annoying when the frequency of false alarms is high. The correlation that we found between rated alarmed response and perceived annoyance also supports previous findings suggesting that annoyance correlates with affect by a factor of approximately 0.6 for increasing emotional activation [25].

Interestingly, however, the differences in subjective ratings were not particularly large. Based on the results of the stimulus evaluation and the significant differences in the warnings' acoustic properties, we had expected larger effects. In fact, a large proportion of the drivers rated both warnings as equally annoying and alarming. One explanation for these results is that both the warning's acoustical properties and its meaning influenced the drivers. Although the signals differed in acoustic characteristics, their function was the same. In urgency ratings, the semantic meaning of auditory warnings has been reported to override acoustic characteristics [9, 13, 14].

Furthermore, McKeown [22] reported that annoyance ratings of in-vehicle warnings could depend on the sound's learnt meaning. One argument for this effect in the present investigation is that the drivers tended to give the high-urgency warning low scores rather than giving the low-urgency warning high scores. The warnings did not indicate a particularly urgent driving situation, and therefore, the low scores for the high-urgency warning make sense. We should point out, however, that the low ratings may also depend on other factors. For instance, the drivers rated their affective reaction to the warnings after they had completed the driving task, not directly after the critical situations. The drivers may not have been able to provide precise ratings of their affective reactions to the warnings after the trial.

Another possible contributing factor to the low subjective scores could be that the commercial drivers, many of whom were experienced, did not find any of the sounds particularly distracting. That is, the warnings may not have had any significant negative impact on the drivers' perceived ability to handle the driving situation. Interestingly, rated annoyance was negatively correlated with driver experience (years of experience) for both types of warnings.

4.2 Brake behaviour

Previous studies have reported that more urgent signals can speed up response time [6, 7, 9]. The present study investigated experienced drivers' responses to road dangers that were not indicated by the auditory warnings. The results can therefore be considered a complement to previous findings. High-urgency warnings might contribute to higher arousal levels, which in turn could negatively affect the drivers' ability to handle unrelated subsequent events. In addition, higher urgency may compel drivers to focus more on the reason of the warning (the pedestrians), which would take their focus away from the road. That is, a high-urgency warning may be more distracting than a low-urgency warning. However, our analysis of brake behaviour did not find a

significant effect on brake response time. The drivers who received the urgent warning in the first critical situation tended to brake later; however, there were large differences between the participants, and we found no significant effect. However, the drivers who received an urgent warning braked significantly harder than the drivers who received the low-urgency warning. It could be argued that the more forceful reactions resulted from higher arousal levels [30] or a stimulus-response compatibility [31]. The correlation between brake pressure and response time indicates that some drivers tried to compensate for late brake responses by braking harder.

Our results might have been different in a study with novice and ordinary car drivers. Chapman and Underwood [29] reported that novice drivers showed longer fixation durations than experienced drivers in critical traffic situations, which indicates that they are less able to share their attention when situations become threatening. Therefore, we recommend that future studies examine the effects of urgent warnings on less experienced drivers.

Another interesting result was that none of the truck drivers made any inappropriate reactions, such as braking without reason, to the auditory signals. Previous research has reported that urgent signals may cause drivers to respond inappropriately to high-urgency warnings [23]. Our findings indicate that commercial truck drivers take their time and assess the road situation before responding to an auditory warning.

5 Conclusion

This study aimed to investigate if the acoustic characteristics that affect urgency also impact perceived annoyance for warnings in commercial vehicles. The results indicate that rated annoyance depends on acoustic properties. However, it seems that acoustic properties alone cannot predict annoyance ratings. A sound's semantic meaning can also have a major impact on annoyance. That is, a driver's rating of a signal as annoying or not depends on the situation that the warning indicates. These results indicate that individual factors, related to driving experience, may also influence rated annoyance associated with warning signals.

Our study's second aim was to investigate if a more urgent sound would have a more significant negative impact on drivers' ability to respond to subsequent unpredictable events. The results showed no significant effect on brake response time and a significant effect on brake response force. The drivers who received a more urgent warning in the first critical situation braked significantly harder for the subsequent unpredictable event. That is, the urgency level of a warning signal may impact commercial drivers' responses to subsequent unpredictable events on the road. However, it remains unclear whether high-urgency warnings can negatively impact the response time. We recommend that future research investigate the negative effects of warning signals on less experienced and novice drivers.

One limitation of the present experiment is related to the auditory warnings that were used. The combination of speech and tone bursts is not a common combination in real-world systems. In addition, the experiment did not provide much information about drivers' perceptions of auditory warnings or their impact on performance as the drivers adjust to them. The results observed in a 25-minute driving test do not allow us to make conclusions about long-term effects and habituation. Finally, conducting tests in simulators has both advantages and disadvantages. An advanced simulator offers a realistic driving experience in a safe and highly controlled setting. However, the driver's awareness of being in a simulator that presents no real danger could potentially threaten the validity of the results.

6 Acknowledgements

The Swedish Excellence centre “Virtual Prototyping and Assessment by Simulation” (ViP), Scania Commercial Vehicle AB, and the Swedish Governmental Agency for Innovation Systems (Vinnova) financed this work. The simulator experiment was carried out in a joint project between the Interactive Institute, Scania Commercial Vehicles, the Swedish National Road and Transport Research Institute (VTI), and Luleå University of Technology.

7 References

- [1] Strandroth, J.: ‘In-depth analysis of accidents with heavy goods vehicles – Effects of measures promoting safe heavy goods traffic’, Swedish Road Administration, Borlänge, Sweden, 2009
- [2] Haas, E., Edworthy, J.: ‘An introduction to auditory warnings and alarms’, in Wogalter, M.S (Ed.): ‘Handbook of Warnings’, (Lawrence Erlbaum Associates, Inc, 2006, 1st edn.), pp. 107-122
- [3] Ho, C., and Spence, C.: ‘Assessing the effectiveness of various auditory cues in capturing a driver’s visual attention’, *Journal of Experimental Psychology: Applied*, 2005, 11, (3), pp. 157-174
- [4] Fung, C.P., Chang, S.H., Hwang, J.R., Hsu, C.C., Chou, W.J., and Chang, K.K.: ‘The study on the influence of auditory warning systems on driving performance using a driving simulator’, Institute of Transportation, Taiwan, Paper no. 07-0170, 2007
- [5] Edworthy, J., Hellier, E., and Walters, K.: ‘The relationship between task performance, reaction time and perceived urgency in nonverbal auditory warnings’ Proc. of IEA 2000/HFEF 2000 Congress, San Diego, CA, USA, 2000
- [6] Haas, E.C., Edworthy, J.: ‘Designing urgency into auditory warnings using pitch, speed and loudness’, *Computing & Control Engineering Journal*, 1996, 7, (4), pp. 193-198
- [7] Haas, E.C., and Casali, J.G.: ‘The perceived urgency and detection time of multi-tone and frequency modulated warning signals’, Proc. of the human factors and ergonomics society 37th annual meeting, Santa Monica, CA, USA, 1993
- [8] Suied, C., Susini, P., and McAdams, S.: ‘Evaluating warning sound urgency with reaction times’, *Journal of Experimental Psychology: Applied*, 2008, 14, (3), pp. 201-212
- [9] Wiese, E.E., and Lee, J.D.: ‘Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance’, *Ergonomics*, 2004, 47, (9), pp. 965-986
- [10] Edworthy, J., Loxley, S., and Dennis, I.: ‘Improving Auditory Warning Design: Relationship between Warning Sound Parameters and Perceived Urgency’, *Human Factors*, 1991, 33, (2), pp. 205-231
- [11] Hellier, E.J., Edworthy, J., and Dennis, I.: ‘Improving auditory warning design: quantifying and predicting the effects of different warning parameters on perceived urgency’, *Human Factors*, 1993, 35, (4), pp. 693-706
- [12] Campbell, J.L., Richard, C.M., Brown, J.L., and McCallum, M.: ‘Crash warning system interfaces: human factors insights and lessons learned’, National Highway Traffic Safety Administration, Washington, DC, USA, 2007, Report No. HS 810 697
- [13] Guillaume, A., Drake, C., Rivenez, M., Pellieux, L., Chastres, V.: ‘Perception of urgency and alarm design’, Proc. of Int. Conf. on Auditory Display 2002, Kyoto, Japan, 2002
- [14] Burt, J.L., Bartolome, D.S., Burdette, D.W., and Comstoc, J.R.: ‘A psychophysiological evaluation of the perceived urgency of warning signals’, *Ergonomics*, 1995, 38, (11), pp. 2327-2340
- [15] Zimmer, K., Ghani, J., and Ellermeier, W.: ‘The role of task interference and exposure duration in judging noise annoyance’, *Journal of Sound and Vibration*, 2008, 311, pp. 1039-

- [16] Block, F.E., Nuutinen, L., and Ballast, B.: 'Optimization of alarms: a study on alarm limits, alarm sounds, and false alarms, intended to reduce annoyance', *Journal of Clinical Monitoring and Computing*, 1999, 15, pp. 75-83
- [17] Khan, M.S., Johansson, O., and Sundback, U.: 'Development of an annoyance index for heavy-duty diesel engine noise using multivariate analysis', *Noise Control Engineering Journal*, 1997, 45, pp. 157-167
- [18] Fucci, D., Petrosino, L., Hallowell, B., Andra, L., and Wilcox, C.: 'Magnitude estimation scaling of annoyance in response to rock music: Effects of sex and listeners preference', *Perceptual and Motor Skills*, 1997, 84, (2), pp. 663-670
- [19] Ellermeier, W., Zeitler, A., and Fastl, H.: 'Predicting annoyance judgements from psychoacoustic metrics: Identifiable versus neutral sounds', *Proc. Of The 33rd International Congress and Exposition on Noise Control Engineering*, Prague, Czech Republic, 2004
- [20] Tan, A.K., and Lerner, N.D.: 'Multiple attribute evaluation of auditory warning signals for in-vehicle crash avoidance systems', *National Highway Traffic Safety Administration – Office of Crash Avoidance Research*, Washington DC, USA, 1995
- [21] Marshall, D.C., Lee, J.D., and Albert Austria, P.: 'Alerts for in-vehicle information systems: annoyance, urgency and appropriateness', *Human Factors*, 2007, 49, (1), pp. 145-157
- [22] McKeown, D.: 'Candidates for within-vehicle auditory displays', *Proc. of Int. Conf. on Auditory Display 2005*, Limerick, Ireland, 2005
- [23] Graham, R.: 'Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application', *Ergonomics*, 1999, 42, (9), pp. 1233-1248
- [24] Baldwin, C.L.: 'Acoustic and semantic warning parameters impact vehicle crash rates', *Proc. of Int. Conf. on Auditory Display 2007*, Montreal, Canada, 2007
- [25] Sköld, A.: 'Integrative Analyses of Perception and Reaction to Information and Warning Sounds in Vehicles', (Chalmers university of technology, 2008)
- [26] Wickens, C.D., and Hollands, J.G.: 'Engineering Psychology and Human Performance', (Prentice Hall, 1999, 3rd edn.)
- [27] Staal, M.A.: 'Stress, Cognition, and Human Performance: A literature review and Conceptual Framework', (Ames Research Center, 2004)
- [28] Kowalski-Trakofler, K.M., Vaught, C., and Scharf, T.: 'Judgment and decision making under stress: an overview for emergency managers', *Int. Journal of Emergency Management*, 2003, 1, (3), pp. 278-289
- [29] Chapman, P.R., and Underwood, G.: 'Visual search of driving situations: Danger and experience', *Perception*, 1998, 27, pp. 951-964
- [30] Jaśkowski, P.J., Rybarczyk, K., Jaroszyk, F., and Lemański, D.: 'The effect of stimulus intensity on force output in simple reaction task in humans', *Acta Neurobiol. Exp.*, 1995, 55, (1), pp. 57-64
- [31] Ulrich, R., and Mattes, S.: 'Does immediate arousal enhance response force in simple reaction time?', *The Quarterly Journal of Exp. Psychology*, 1996, 49A, (4), pp. 972-990

PAPER 3

Fagerlönn, J. (2011). Making auditory warning signals informative: examining the acceptance of auditory icons as warning signals in trucks. In *Proceedings of the 6th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 95-101). Iowa City: University of Iowa.

MAKING AUDITORY WARNING SIGNALS INFORMATIVE: EXAMINING THE ACCEPTANCE OF AUDITORY ICONS AS WARNING SIGNALS IN TRUCKS

Johan Fagerlönn
Interactive Institute – Sonic Studio
Piteå, Sweden
johan.fagerlonn@tii.se

Summary: Auditory icons have the potential to enhance a driver's situation awareness, to reduce his or her visual load, and to improve his or her response time in an emergency situation. However, the level of acceptance of this type of auditory signal as a warning signal is not well understood. The present study was carried out to investigate truck drivers' initial acceptances of auditory icons as warnings. The drivers selected warning signals for a number of dangerous driving situations. A method that was based on subjective ratings was also used to assess the drivers' acceptances of the sounds and to gain a better understanding of the factors that influence the drivers' selections. The results showed that the level of acceptance can be very high, but it varied significantly among the auditory icons that were encountered in five driving situations. Perceived "usefulness" and "satisfaction" may be used to determine whether the drivers prefer an auditory icon in specific situations. However, the subjective ratings related to the satisfaction should be complemented with a deeper qualitative investigation when examining the acceptance of auditory icons as warnings.

INTRODUCTION

Auditory warnings and alerts are now commonly implemented in advanced driver assistance systems (ADASs). Signals that include sound have unique advantages over visual options in emergency situations. Hearing is omnidirectional, while visual warnings must be seen [1]. However, whereas simple auditory signals are used to attract attention, the detailed information is most often presented visually, either outside in the traffic environment or inside the vehicle through visual displays.

The concept of auditory icons was first introduced by Gaver (1986). He defined them as "everyday sounds mapped to computer events by analogy with everyday sound-producing events". Auditory icons differ from other non-verbal sounds in user interfaces in that they sound like what they represent, which tends to make auditory icons meaningful in the context in which they are presented. In contrast, conventional warnings are arbitrarily mapped to their alarming function. Previous research has shown that auditory icons are easy to learn and interpret compared to other non-verbal signals (Leung, Smith, Parker and Martin, 1997; Dingler, Lindsay and Walker, 2008; Fagerlönn and Alm, 2009). Auditory icons may also lead to

faster driver responses in urgent situations compared to simple tones and speech messages (Graham, 1999). Belz, Robinson and Casali (1999) reported that truck drivers respond significantly more quickly to auditory icons compared to repetitive tone pulses in a collision situation. Additionally, meaningful sounds can enhance safety by amplifying the driver's awareness of his or her surroundings (Chen, Qvint and Jarlengrip, 2007) without adding to his or her visual load. One potential issue with the use of auditory icons as warnings is that the level of acceptance of these sounds may be low. Belz et al. (1999) reported that about half of the participating truck drivers were sceptical about the use of auditory icons, indicating that they did not consider these signals to be serious warnings in commercial vehicles. Thus far, little research has focused on drivers' acceptances of auditory icons as warning signals for commercial vehicles. The acceptance of warning signals may depend largely on factors that are not directly related to the sound, such as the rate of false warnings (Block, Nuutinen and Ballast, 1999). However, investigating the initial acceptance of the auditory signal is important. Drivers who do not find a sound appropriate may turn it off or even reject the system. However, if the level of acceptance is very high, that can also be valuable information for developers intending to implement auditory warning signals in future ADASs. Furthermore, if designers plan to use auditory icons in warning systems, we must know more about the perceived qualities of these systems that impact the acceptance of these sounds as warning signals. One aim of the present investigation was to study commercial drivers' initial acceptances of auditory icons for conveying information in potentially dangerous driving events. A second aim was to examine the underlying factors that affect the acceptance of auditory icons as warning signals in trucks.

METHODS

In the present study, I used two complementary methods. In the first method, drivers selected warning signals for five driving situations using a visual interface. In the second method, I used a procedure described by Van der Laan, Heino and de Waard (1996) to assess the drivers' acceptances of the auditory icons in each of the five driving situations.

Twenty-two truck drivers (2 females and 20 males) between the ages of 23 and 63 years (mean age: 38.4 years; SD: 12.3 years) participated. They reported an annual driving distance between 10,000 and 250,000 km (mean: 94,410 km; SD: 53,640 km). All of the drivers reported normal hearing.

The trials were conducted inside of a Scania R truck cabin. The interface PART (Liljedahl and Fagerlönn, 2010) was back-projected 2.90 metres in front of the cabin. The experimenter could control this interface from inside the cabin. The interface showed videos of driving situations, and the participants could control the playback of these videos via the experimenter. They were also able to choose the exact point in the video at which a warning should be triggered. Another part of the interface was used to select the auditory warnings for the driving situations. The drivers could choose from 162 variants of arbitrary warning signals. These signals were arbitrary in the sense that they were not designed to convey any specific meaning to the drivers about any of the driving situations. They were all pulses of sounds that were played in a distinct pattern. Their lengths ranged from 0.5 to 1.2 s. The participants could also select one of three warning modes for each driving situation. If the participant selected the "no warning sound" mode, no warning sound was played in that situation. If they selected the "arbitrary" mode, then the arbitrary sound was triggered at the indicated point in the video. If the "arbitrary + auditory icon" mode was selected, the brief arbitrary sound was first triggered, and then an auditory icon was played to give information

about the situation. The auditory signals were presented using a 5.1 speaker system (Anthony Gallo Acoustics Inc, CA, USA). I used background noise that was recorded inside a Scania truck travelling at a speed of 60 km/h during the trials. The background noise was calibrated to approximately 61 dBA at the driver's position.

The driving situations were staged and recorded from inside a Scania R truck near Stockholm, Sweden. In the "lane departure" situation, the driver was travelling on a straight three-lane motorway. After some time, the truck started to drift slowly to the left into the next lane. The auditory icon representing this situation was a low-frequency rumble noise, similar to tires on road grooves. In the "collision" situation, the truck was driving on a straight road. A passenger car, initially hidden behind terrain and vegetation, approached an intersection from a connecting road. The car suddenly became visible and began to pull out in front of the truck. This situation was represented by a car horn. In the "slippery road" situation, the driver was heading into a curve on a slippery road. This situation was represented by the sound of ice scraping. In the "cyclist" situation, the driver was heading toward an intersection with the intention to turn right. A cyclist caught up with the truck on the right side and stopped in the blind spot. The driver then started to turn right. The sound of a bicycle bell was used to represent this situation. In the "traffic queue" situation, the truck was driving on a motorway entrance. There was a traffic queue on the motorway, and the driver had to brake to avoid a collision. This situation was represented by a number of horns playing simultaneously.

The drivers were told that the objective of the study was to investigate commercial drivers' attitudes towards the use of auditory signals for a range of in-vehicle systems. They were introduced to the visual interface that displayed the driving situations. The drivers were instructed to select warning sounds for the driving situations. They were told to select options that they would prefer to have appear in a truck while driving. While making their selections, the drivers were allowed to suggest any alternative solutions. For example, if they preferred a visual display instead of a warning sound, they were allowed to suggest the use of a visual sign. After the subjects felt satisfied with their selections, they listened to the auditory icons again. The participants were then required to rate each representative sound according to the procedure, as recommended by Van der Laan et al. (1996). The participants made judgements about their experiences of the sounds using nine, five-point rating scale items. The items were related to two scales; one scale denoted the perceived usefulness, and one scale designated the perceived satisfaction. The scales that were related to usefulness assessed the following values: worthless/assisting, useless/useful, superfluous/effective, sleep-inducing/raising alertness and bad/good. The scales related to satisfaction assessed the following values: unpleasant/pleasant, undesirable/desirable, irritating/likeable and annoying/nice. The nine rating items were presented in a mixed order. The drivers' selections of the warning modes during sound selection and the usefulness and satisfaction scores that were associated with the auditory icons in the five driving situations defined the dependent measures in the evaluation.

RESULTS

Figure 1 shows the drivers' selections of the sounds for the different driving situations. Considerable differences were observed in the drivers' selections of the warning modes for the five driving situations. In the "lane departure" and "cyclist" situations, 18 and 17, respectively, of the 22 participants selected an auditory icon. In the other driving situations, only 5-7 participants selected an auditory icon.

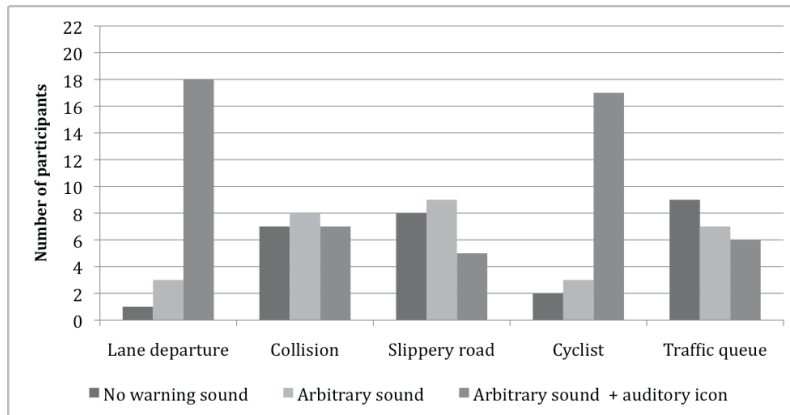


Figure 1. The subjects' selections of the warning modes for the five driving situations

Subjective ratings

Table 1 shows the mean subjective scores, standard deviations, reliability measures and correlations for the subjective ratings.

Table 1. Results of the subjective ratings. Standard deviations (SD) are presented in parenthesis. Correlations are for the usefulness and satisfaction scores, Pearson's correlation coefficient (two-sided test). * $p < 0.01$

	Lane departure	Collision	Slippery road	Cyclist	Traffic queue
Usefulness (SD)	1.23 (0.70)	-0.18 (1.28)	-0.60 (1.20)	0.53 (1.39)	-0.30 (1.11)
Worthless – assisting	1.27 (0.70)	-0.09 (1.54)	-0.64 (1.36)	0.50 (1.60)	-0.27 (1.35)
Useless – useful	1.27 (0.55)	0.00 (1.45)	-0.36 (1.40)	0.59 (1.56)	-0.18 (1.40)
Superfluous –effective	1.18 (1.05)	-0.64 (1.40)	-0.68 (1.36)	0.41 (1.50)	-0.59 (1.18)
Sleep-inducing - raising alertness	1.23 (0.97)	0.18 (1.40)	-0.50 (1.34)	0.73 (1.42)	-0.23 (1.07)
Bad – good	1.23 (0.81)	-0.36 (1.40)	-0.82 (1.37)	0.41 (1.47)	-0.23 (1.19)
Satisfaction (SD)	-0.05 (0.67)	-0.34 (0.95)	-0.76 (-1.05)	0.06 (1.23)	-0.43 (0.93)
Unpleasant – pleasant	-0.36 (0.85)	-0.05 (1.13)	-0.59 (1.26)	0.14 (1.13)	-0.27 (1.03)
Undesirable – desirable	1.00 (0.87)	-0.55 (1.37)	-0.91 (1.31)	0.18 (1.53)	-0.50 (1.30)
Irritating – likeable	-0.73 (0.98)	-0.41 (1.05)	-0.91 (1.02)	-0.09 (1.27)	-0.55 (1.10)
Annoying - nice	-0.09 (1.27)	-0.36 (1.22)	-0.64 (1.40)	0.05(1.29)	-0.41 (1.05)
Cronbach's α useful. / satisf.	0.89/0.59	0.82/0.81	0.93/0.86	0.95/0.95	0.94/0.84
Correlation useful. – satisf.	0.26	0.75*	0.86*	0.93*	0.94*

The scores ranged between -2 and +2. The reliability tests for the items related to the usefulness and satisfaction resulted in Cronbach's alpha values (above 0.65, as recommended by Van der Laan et al. 1996) for all situations, except for the satisfaction component in the "lane departure" situation. I found that the auditory icons for the "lane departure" and "cyclist" situations received the highest usefulness and satisfaction scores. However, none of the sounds received particularly high satisfaction scores. I used a one-way ANOVA to

investigate the differences in the subjective ratings between the auditory icons for the five driving situations. Significant differences were found for the usefulness scores $F(4,84)=14.1$, $p<0.01$ and the satisfaction scores $F(4,84)=3.53$, $p<0.01$. The post-hoc analyses using Tukey's honestly significant difference (HSD) test revealed that the usefulness score for the "lane departure" situation was significantly higher than the scores for the sounds in the other situations ($p<0.01$), except for the auditory icon in the "cyclist" situation. Tukey's HSD test also revealed that the usefulness score for the "cyclist" situation was significantly higher than the scores for the "slippery road" ($p<0.01$) and "traffic queue" ($p<0.05$) situations. The satisfaction scores for the "lane departure" and "cyclist" situations were significantly higher than that for the "slippery road" situation ($p<0.05$). Interestingly, I found strong positive correlations between the usefulness and satisfaction scores for the sounds in four of the five driving situations (Pearson, $r = 0.75-0.94$, $p<0.01$, two-sided), indicating that the drivers who found the sound useful also found it satisfying (and vice versa).

Comparing drivers' selections and subjective scores

The two most selected auditory icons received significantly higher usefulness scores compared to the sounds for the other situations. I used a univariate logistic regression analysis to investigate the associations between the drivers' selections and the usefulness and satisfaction scores. The results of the analysis are shown in Table 2. I found that both components were significant predictors of the drivers' selections in two of the five driving situations. The odds ratios (ORs) higher than 1.0 indicated that the drivers that gave a sound a high score were more likely to select the sound in the selection task. The results indicate that the usefulness and satisfaction scores are appropriate predictors to determine whether a driver prefers an auditory icon as a warning signal. I found no significant association between the usefulness and satisfaction scores and the drivers' selections for the "lane departure" situation (only four drivers did not select the auditory icon for this situation).

Table 2. Results from the logistic regression analysis. OR, odds ratio; CI, confidence interval. * $p<0.05$. ** $p<0.01$

	Usefulness			Satisfaction		
	OR	95% CI	p-value	OR	95% CI	p-value
Lane Departure	0.84	0.157-4.48	0.830	1.05	0.20-5.44	0.95
Collision	3.96	1.20-13.03	0.024*	2.82	0.75-10.58	0.124
Slippery Road	2.25	0.90-5.66	0.082	3.74	1.03-13.59	0.045*
Cyclist	4.07	1.33-12.49	0.014*	5.47	1.37-21.63	0.016*
Traffic Queue	9.3	1.10-79.05	0.002**	23.58	1.19-466.41	0.038*

Demographic data and subjective ratings

Investigating the relationships between the demographic data (age and annual driving distance) and the subjective responses was not the primary aim of the present study. However, I found a positive significant correlation between the usefulness scores for the "lane departure" situation and the drivers' annual driving distance (Spearman, $r = 0.54$, $p<0.01$, two-sided). The auditory icon for this situation received the highest usefulness score, and it was interesting that the drivers who drive the most tended to rate the sound particularly useful.

DISCUSSION

The results of the sound selection task indicate that the level of acceptance was high for the auditory icons in two of the situations but that there was a considerable variation between the auditory icons for the different driving situations. Many of the drivers selected auditory icons in the "lane departure" and "cyclist" situations. In addition, an analysis of the subjective ratings revealed significant differences in the subjective scores for the auditory icons, especially in terms of the usefulness. The results suggest that system developers should seriously consider the use of auditory icons when implementing warning systems. Not only could auditory icons become very effective warning signals, but drivers may also show a high level of initial acceptance of these sounds.

I also found that the usefulness and satisfaction scores can be used to determine whether an auditory icon is preferred in a driving situation. The most frequently selected auditory icons received significantly higher usefulness scores compared to the auditory icons in the other situations. This result indicates that perceived usefulness may be an especially important quality for auditory icons when presented as warning signals in trucks. None of the auditory icons received particularly high satisfaction scores. However, the positive correlations that were observed between the usefulness and satisfaction scores for four of the five driving situations indicate that the two components are closely related. Furthermore, the logistic regression analysis revealed that the satisfaction score was a significant predictor of the drivers' selections for three of the driving situations. Therefore, a low level of perceived satisfaction is most likely a negative quality of auditory icons as warning signals in commercial vehicles.

Three of the four rating items that comprise the satisfaction component (pleasant/unpleasant, irritating/likeable and annoying/nice) are related to perceived annoyance. Previous research has found that a high level of annoyance is an inappropriate quality for low urgency warnings but not necessarily for high urgency warnings (Marshall, Lee and Austria, 2007). Additionally, McKeown (2005) investigated the annoyance of auditory icons for in-vehicle use and found that drivers consistently rated auditory icons that were mapped to more urgent situations as being more annoying. With these previous results in mind, it was a bit surprising that higher satisfaction scores were obtained for the dangerous "cyclist" situation. In contrast, I found that the auditory icon for the very dangerous "lane departure" situation was considered to be irritating and unpleasant rather than likeable and pleasant. Furthermore, no significant correlations were found between the usefulness and satisfaction scores for this particular auditory icon. Some of the participants may have rated this sound as irritating and unpleasant because the sound indicated a very dangerous situation. In summary, it is a challenge to interpret the satisfaction scores of the auditory warnings. It may not be sufficient to ask the participants whether they find a particular sound annoying, irritating or unpleasant, etc. To make more valid judgements about the level of acceptance, we must also ask the subjects why they rate the sound in such a way, and whether their rating indicates a good or bad quality of the particular signal.

The popular auditory icon that was presented in the "lane departure" situation was considered useful, especially by drivers that reported a high annual driving distance. I recommend that future research should investigate how the acceptance of auditory icons can depend on the individual characteristics of drivers. A better understanding of the individual differences would have implications for the system designers that intend to offer personal settings for in-vehicle warning signals. Furthermore, it is likely that the drivers' attitudes will

change over time, for example, if the drivers found a signal helpful. Future studies should investigate the acceptance of auditory icons after their prolonged use.

ACKNOWLEDGMENTS

The Swedish Information and Communication Technology Research (Swedish ICT) and Scania CV AB financed this work. Special thanks to Håkan Alm at Luleå University of Technology, and Robert Friberg and Anna Sirkka at Scania CV AB.

REFERENCES

- Block. F.E., Nuutinen. L., & Ballast. B. (1999). Optimization of alarms: a study on alarm limits, alarm sounds, and false alarms, intended to reduce annoyance. *Journal of clinical monitoring and computing*, 15, 75-83.
- Belz. S.M., Robinson. G.S., & Casali. J.G. (1999). A new class of auditory warning signals for complex systems: auditory icons. *Human Factors*, 41(4), 608-618.
- Chen. F., Qvint. G., & Jarlengrip. J. (2007). Listen! There are other road users close to you - improve the traffic awareness of truck drivers. In C. Stephanidis (Ed.), *Universal Access in Human Computer Interaction. Ambient Interaction* (pp. 323-329). Heidelberg: Springer.
- Dingler. T., Lindsay. J., & Walker. B. (2008). Learnability of sound cues for environmental features: auditory icons, earcons, spearcons and speech. *Proceedings of ICAD 2008*, Paris.
- Fagerlönn, J., & Alm. H. (2009). Auditory signs to support traffic awareness. *Proceedings of the 16th World Congress on Intelligent Transport Systems*, Stockholm.
- Gaver. W.W. (1986). Auditory icons: Using sound in computer interfaces. *Human-computer Interaction*, 2(2), 167-177.
- Graham. R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application. *Ergonomics*, 42(9), 1233-1248.
- Haas. E., & Edworthy. J. (2006). An introduction to auditory warnings and alarms, in M.S. Wogalter (Ed.), *Handbook of Warnings* (pp. 189-198). Mahwah: Lawrence Erlbaum Associates, Inc.
- Leung, Y.K., Smith. S., Parker. S., & Martin. R. (1997). Learning and Retention of Auditory Warnings. *Proceedings of ICAD 1997*, Paolo Alto.
- Liljedahl, M., and Fagerlönn, J. (2010). Methods for Sound Design: A Review and Implications for Research and Practice. *Proceedings of Audio Mostly 2010*, Piteå.
- Marshall. D.C., Lee. J.D., and Austria. P.A. (2007). Alerts for in-vehicle information systems: annoyance, urgency and appropriateness. *Human Factors*, 49(1), 145-157.
- McKeown. D. (2005). Candidates for within-vehicle auditory displays. *Proceedings of ICAD 2005*, Limerick.
- Van der Laan. J.D., Heino. A., & de Waard. D. (1996). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research C*, 5(1), 1-10.

PAPER 4

Fagerlönn, J. The design of auditory warning signals: what are the opinions of vehicle developers and truck drivers? In preparation to be submitted to an international journal or conference.

The design of auditory warning signals: what are the opinions of vehicle developers and truck drivers?

Johan Fagerlönn

Interactive Institute - Sonic Studio, SE-94128, Piteå, Sweden, johan.fagerlonn@tii.se.

Keywords: warnings, alarms, interface design, driver distraction, safety

Abstract: Auditory warning signals are becoming increasingly common in Intelligent Transport Systems (ITSs). Carefully designed auditory signals may contribute to more effective and safe multimodal interfaces in future ITSs. However, inappropriate sounds could undermine driver performance, safety and system acceptance. Today, much of the responsibility for designing auditory warnings lies in the hands of vehicle developers working in the industry. The nature of the auditory solutions that will be seen in future vehicles depends on the developers' opinions about how auditory warnings should be designed. A questionnaire study was conducted to gather the views of vehicle developers and professional truck drivers on potentially important attributes of in-vehicle warning signals. The results show that both developers and drivers ranked many of the investigated warning attributes as very important. For instance, both groups agree that it is very important that warnings are easy to understand and prepare the driver to respond. These results are interesting, considering that most auditory warnings currently used in vehicles are simple sounds that do not convey any meaning about the situation. The results also indicate that some developers may be prone to use a "better safe than sorry" strategy when designing high-urgency warnings. Many developers considered it unimportant if a high-urgency warning sound is perceived as annoying, and some developers considered it unimportant if a high-urgency warning is too startling. Furthermore, the results indicate that the perceived importance of the warning signal attributes depends on the urgency of the situation. Finally, a number of significant differences found between the developer and driver ratings suggest that experienced drivers should be invited to take part in the warning signal design process.

1 Introduction

Auditory warning signals are now commonly used in Intelligent Transport Systems (ITSs). Sound has unique advantages over other modes of communication, especially in urgent situations that require immediate attention. A fundamental function of auditory warning signals is to catch the driver's attention so that the sound is consciously perceived. However, research has shown that well-designed verbal and non-verbal auditory signals can have functionality beyond simply grabbing the driver's attention. If system developers take advantage of the full potential of auditory warnings, we might see more effective, safe and tolerable vehicle interfaces in the future. In contrast, carelessly implemented auditory signals may negatively affect performance, safety and system acceptance.

In the present article, I start by presenting a number of properties of auditory warnings that should be considered by vehicle developers. I then present a study conducted to investigate the opinions of vehicle developers and professional drivers on auditory warning design, i.e., which attributes of auditory warnings do vehicle developers and professional drivers consider important? Finally, I discuss the results by identifying promising observations and potential concerns related to auditory warning design for ITSs in the future.

1.1 Meaning

Most auditory warning signals are very simple sounds, such as a distinct repeated pattern of tones or simple “beeps”. While these sounds do catch drivers’ attention, detailed information is generally presented on visual displays. However, research has established that verbal and non-verbal signals can be useful carriers of driving-related information [1-4]. Conveying information via auditory channels in a vehicle is an interesting concept, especially in demanding driving situations, because it allows drivers to stay visually focused on the road. Research has also shown that auditory warnings that are easily learnt and interpreted by drivers may be more effective warnings than traditional abstract sounds, leading to decreased response times [1-4], fewer errors [1,3] and even reduced annoyance [3]. Short verbal messages (keywords) and auditory icons (real-world sounds) that are easily associated with the alarming situation may be especially effective.

1.2 Orienting responses

Sounds that are presented from a particular spatial direction may effectively guide a driver’s attention towards the danger. However, sounds that are played from inappropriate spatial directions may cause disorienting responses and lead to unnecessarily long response times [5]. Orienting responses towards the source of the auditory cues could be both voluntary and involuntary [6,7]. That is, salient auditory cues triggered from inappropriate spatial directions inside a vehicle may unnecessarily and even unavoidably distract the driver.

1.3 Perceived urgency

Matching the urgency of a warning to the urgency of a situation has been referred to as “urgency mapping” [8]. A body of research has established that the perceived urgency depends on both the temporal and spectral properties of the warning such as pitch, speed and amplitude envelope [8-10]. The perceived urgency also depends on the listener’s “mental representation” of the warning’s cause [11], and this mapping could override acoustic characteristics [12]. Appropriate “urgency mapping” could help drivers to prioritise driving-related tasks more effectively. It has been argued that appropriate urgency mapping can reduce workload [13], but inappropriate “urgency mapping” may have the opposite effect and confuse the driver. For instance, if a driver perceives a collision warning as less urgent than a signal for vehicle failure or an incoming e-mail, she or he is likely to be confused.

1.4 Emotional responses

It is well known that salient sounds have the potential to invoke strong emotional responses involving subjective feelings and increased physiological arousal. According to Västfjäll et al. [14], emotional reactions to danger can be triggered rapidly and automatically by sounds whose acoustic properties indicate a threat in the environment. If the sound does not possess such acoustic properties, it will be compared with sound memories stored in the person’s long-term memory. If the sound is judged as unknown or if it is associated with something dangerous, it will also trigger an emotional response.

High-urgency auditory warnings could potentially also contribute to increased arousal in more indirect ways. Perceived urgency can lead to a feeling of time pressure, which in turn can increase arousal. A certain amount of physiological arousal is probably appropriate in an urgent driving situation. A possible effect of arousal is attentional narrowing [15,16]; in other words, the individual’s focus of attention shrinks, and he or she focuses on potentially important elements in the environment [17]. Sounds that can interrupt ongoing cognitive processes, make the listener

focus attention on the important events and respond quickly, may act as effective warnings. Consequently, researchers have investigated how warnings can be designed to evoke appropriate emotional responses in listeners [18,19]. However, attention narrowing may not be appropriate in demanding driving situations that require the driver to share attention among several ongoing tasks and events.

Furthermore, it has been reported that warning signal parameters that increase the perceived urgency also have a tendency to raise annoyance levels [1,10,20]. Annoyance is an important consideration for warning design because of the risk that the user will turn off the sound or neglect the system. The potential of urgent auditory warnings to become annoying has led researchers to suggest an “urgency-annoyance trade-off” when implementing auditory warnings [13]. In addition, if vehicle developers apply a “better safe than sorry” approach to warning design and use extreme sounds (e.g., very loud, sudden sounds), there is a risk is that the sound will not only negatively impact acceptance but also trigger a severe startled reaction that could interfere with an urgently required action.

1.5 Audibility and separability

For an in-vehicle auditory warning to be effective, it must be audible in the acoustic environment. Auditory masking refers to a process where one sound is rendered inaudible because of the presence of another sound [21]. Two different types of masking exist, simultaneous and non-simultaneous masking [21]. Simultaneous masking is a frequency-domain phenomenon in which a lower-level signal can be made inaudible by a simultaneous higher-level signal if the frequencies of the two sounds are sufficiently similar. One way to prevent simultaneous masking is to adjust the frequency content and/or level of the warning sound so that it will not be masked. The National Highway Traffic Safety Administration (NHTSA) guidelines from 1996 [22], for instance, suggest that the intensity of an in-vehicle crash avoidance warning should be at least 20 dB of sound pressure level (SPL) above the masking threshold. Another technique to reduce simultaneous masking might be to remove the potential masker, for instance, to mute the in-vehicle radio system when a warning signal is played. Non-simultaneous masking can occur when two sounds appear within a small interval of time. Two types of non-simultaneous masking exist: pre-masking and post-masking. Post-masking (which has a significantly longer duration than pre-masking) implies that the masking effect does not immediately stop after the masker is removed. For example, the audibility of a low-level warning might be negatively affected by the presence of a high-level warning played immediately before the low-level warning.

Interpretation of a warning can also be negatively affected when the signal cannot be clearly distinguished from other sounds. For instance, a speech message may be confused with a voice from the radio. Warning signals that sound too similar may also be confused with each other. Conventional warnings often have some typical characteristics. For example, they can be synthetic tones played in a distinct pattern. These types of signals may not be sufficiently unique to allow a driver to separate one warning sound from another.

1.6 The study

Decisions regarding auditory warning design are made by developers working in the vehicle industry. The characteristics of the auditory warnings depend on the developers’ awareness of the potential benefits and issues that the auditory domain offers. So far, very little research has investigated developers’ opinions about auditory signals. In 1995, Tan and Lerner [20] examined developers’ opinions regarding a wide range of characteristics of an imminent crash avoidance warning. However, much has happened in the vehicle domain and specifically in the development

of ITSs since that time. Furthermore, ITSs may use auditory warnings in a wide range of situations, not only for urgent warnings such as crash avoidance warnings.

Furthermore, it is also of interest to learn what experienced drivers consider important characteristics of auditory warning signals. Professional drivers typically have experience in demanding and urgent driving situations and can provide insight regarding appropriate and inappropriate warning signals. The insight of experienced drivers' opinions may guide both researchers and system developers to find auditory warnings that meet with higher acceptance.

1.6.1 Objectives

The present study investigated the following three research questions:

- Which attributes of auditory warning signals do vehicle developers and commercial drivers consider important?
- Are there differences in the developers' opinions regarding warning signals of different levels of urgency?
- Are there differences between the opinions of vehicle developers and those of professional drivers?

2 Methods

In 2010, a questionnaire was designed (based on the questionnaire by Tan et al. [20]) and distributed to vehicle developers and professional drivers in Sweden. The questionnaire was divided into three main parts. In the first part, the respondent provided demographic information. In the second and third parts, respondents were introduced to two different driving situations (one situation in each part). The two driving situations were selected to present significantly different levels of perceived urgency. In the "high-urgency situation", the respondents were asked to imagine the vehicle being about to collide with another vehicle or object in the traffic environment. In the "low-urgency situation", the participants were asked to imagine a situation in which a school bus had stopped 400 meters ahead of the vehicle to pick up or drop off passengers. In each situation, the participants were asked to respond to statements regarding the importance of a range of warning attributes, see Table 1.

Table 1 *The statements used in the questionnaire. They were based on the statements used in the questionnaire by Tan et al. [20].*

Warning attribute	Statement in the questionnaire
Appropriate orienting response	The warning is easily localised by the driver and makes the driver shift attention towards the warning's cause
Not annoying	The warning is not annoying
Prepares the driver to respond	The warning prepares the driver to respond
Appropriate urgency level	The warning does not sound too urgent or too calm considering the warning's cause
Clearly audible	The warning is clearly audible while driving
Easy to understand	The driver can easily understand what the warning means
High acceptance	The warning is accepted by the driver
Not too startling	The warning is not too startling
Easy to distinguish	The warning is easy to distinguish from other sounds in the truck

Responses were graded on a Likert scale ranging from 1 (not at all important) to 5 (very important). Two versions of the questionnaire were designed. In one version, the high-urgency situation was presented in the second part of the questionnaire, and the low-urgency situation was presented in the third part. In the other version, the high-urgency situation was presented in the third part and the low-urgency warning in the second part. Each version of the questionnaire was distributed to 50% of the vehicle developers and 50% of the drivers.

2.1 Participants

The questionnaire was personally handed out or mailed to 50 vehicle developers and 76 professional truck drivers. The developers were either employees at the company Scania CV AB in Sweden or hired technical consultants currently working within the Scania CV AB organisation. The developers worked with various aspects of vehicle design such as interface design, cognitive ergonomics, and system programming, but not necessarily with audio design. 50 of the 76 truck drivers were employees at a haulage firm in Sweden run by Scania CV AB. The other 26 drivers worked at various haulage firms in Sweden. In total, 36 questionnaires were returned from developers and 45 from drivers. However, two of the questionnaires received from developers and four of those received from drivers were incomplete and were discarded from further analysis. The final response rates (completed questionnaires) were 68 % for developers and 54 % for drivers. The ages of the responding developers (28 males, 6 females) ranged from 21 to 50 years ($M=34.2$, $SD=6.9$). The ages of the responding drivers (35 males, 6 females) ranged from 22 to 63 years ($M=43.6$, $SD=11.4$), and the drivers' years of truck driving experience ranged from 0.5 to 45 years ($M=17.6$, $SD=12.3$).

3 Results

3.1 Vehicle developers

Figure 1 shows the mean scores of the vehicle developers' subjective ratings. Most warning attributes received high mean scores (above 4.0) in both the high-urgency situation and the low-urgency situation. The only attribute that received a low mean score was "not annoying" in the high-urgency situation ($M=2.09$, $SD=1.29$). A large portion of the developers (41%) rated "not annoying" to be not at all important in the high-urgency situation. The attributes "appropriate urgency level" ($M=3.47$, $SD=1.33$) and "not too startling" ($M=3.24$, $SD=1.16$) received moderate mean scores in the high-urgency situation. A more detailed investigation showed that the attribute "appropriate urgency level" was rated to be not at all important by 15 % of the developers, and the attribute "not too startling" was rated to be not at all important by 12 % of the developers. All other attributes received very high mean scores ($M=4.00-4.83$, $SD=0.47-1.05$) in the high-urgency situation. In the low-urgency situation, all nine attributes received high mean scores ($M=4.08-4.58$, $SD=0.55-0.90$).

A comparison between the mean scores in the two driving situations shows that the attributes "not annoying" and "not too startling" were considered to be considerably more important in the low-urgency situation than in the high-urgency situation. The attributes "appropriate urgency level" and "high acceptance" had slightly higher mean ratings in the low-urgency situation. The mean scores of the attributes "appropriate orienting response", "prepares the driver to respond", "clearly audible", "easy to understand" and "easy to distinguish" were slightly higher in the high-urgency situation than in the low-urgency situation. I did not assume that the data were normally distributed. Wilcoxon signed-rank tests were used to investigate the differences in the scores in the two driving situations. Significant differences were found for the attributes "appropriate orienting response"

($W=105$, $z=2.97$, $p=.00$, two-tailed), “not annoying” ($W=-351$, $z=-4.45$, $p=.00$, two-tailed), “prepares the driver to respond” ($W=172$, $z=3.45$, $p=.00$, two-tailed), “appropriate urgency level” ($W=-126$, $z=-2.34$, $p=.02$, two-tailed) “clearly audible” ($W=171$, $z=3.71$, $p=.00$, two-tailed), “not too startling” ($W=-387$, $z=-4.18$, $p=.00$, two-tailed), and “easy to distinguish” ($W=110$, $z=2.59$, $p=.00$, two-tailed). The differences in the attributes “high acceptance” ($W=-83$, $z=-1.80$, $p=.07$) and “easy to understand” ($W=49$, $z=1.52$, $p=.13$, two-tailed) between the driving situations were not significant at the $\alpha = 0.05$ level.

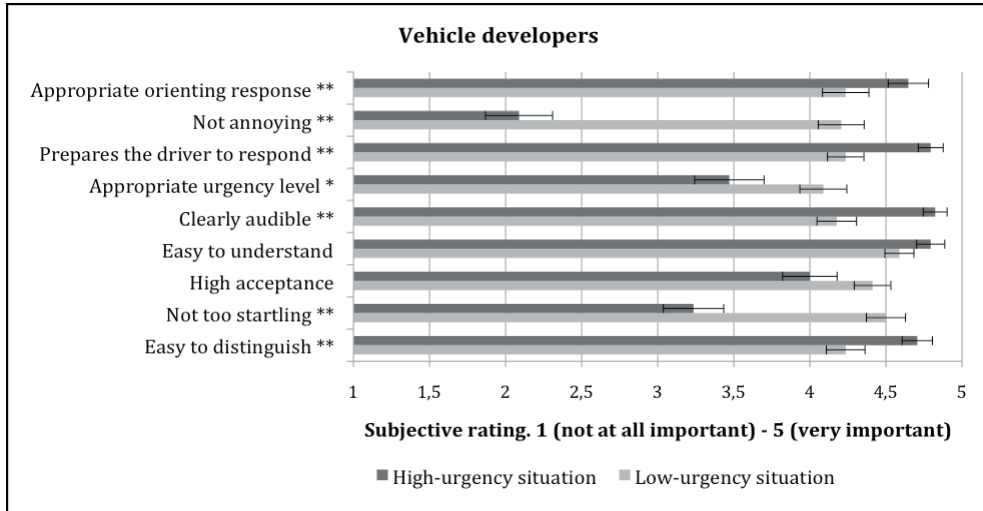


Figure 1 The vehicle developers’ subjective ratings. Error bars show standard errors. Two-tailed Wilcoxon signed-rank tests were used to investigate the differences between driving situations, * $p < 0.05$, ** $p < 0.01$.

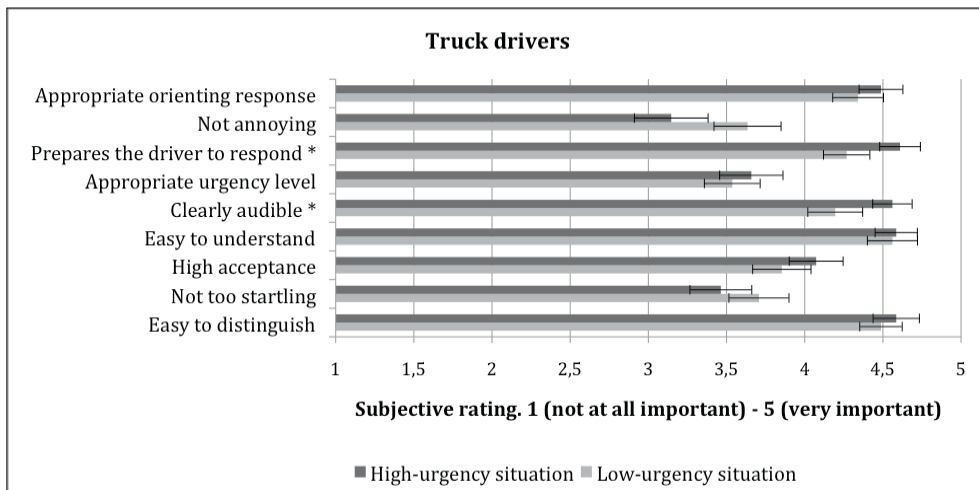


Figure 2 The professional truck drivers’ subjective ratings. Error bars show standard errors. Two-tailed Wilcoxon signed-rank tests were used to investigate the differences between the two driving situations, * $p < 0.05$.

3.2 Truck drivers

Figure 2 shows the mean scores for the professional truck drivers' subjective ratings. The mean scores of all warning attributes were intermediate or high in both the high-urgency situation ($M=3.15-4.61$, $SD=0.81-1.51$) and the low-urgency situation ($M=3.54-4.56$, $SD=0.87-1.37$). The attribute "not annoying" in the high-urgency situation received the lowest mean score ($M=3.15$, $SD=1.51$), with 20 % of the drivers rating that attribute to be not at all important. A comparison between the mean ratings in the two driving situations revealed no considerably large differences in the rankings of any of the warning attributes. Wilcoxon signed-rank tests revealed significant differences between the two driving situations for the attributes "prepares the driver to respond" ($W=93$, $z=2.19$, $p=.03$, two-tailed) and "clearly audible" ($W=62$, $z=2.41$, $p=.02$, two-tailed). No significant differences were found for the other attributes in the two situations. However, the difference for the attribute "not annoying" was very close to being significant ($W=-113$, $z=-1.96$, $p=.05$, two-tailed).

3.3 Comparison between vehicle developers and truck drivers

Figure 3 shows the mean ratings of both groups in the high-urgency situation. The mean score for the attribute "not annoying" was considerably higher for the drivers ($M=3.15$, $SD=1.51$) than for the developers ($M=2.09$, $SD=1.29$). A Mann-Whitney U test revealed that the difference was significant ($U=971.5$, $z=-2.92$, $p=.00$, two-tailed). No other significant differences between the two groups were found at the $\alpha = 0.05$ level.

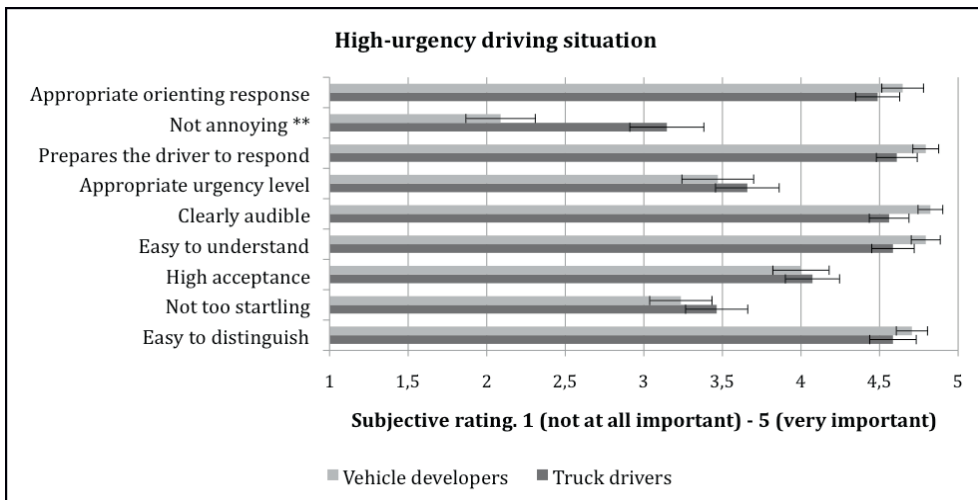


Figure 3 Mean ratings in the high-urgency driving situation. Error bars show standard errors. Two-tailed Mann-Whitney U tests were used to investigate differences between the two groups, $** p < 0.01$.

Figure 4 shows the mean ratings of both groups in the low-urgency situation. The attribute "easy to understand" received the highest mean score from both system developers and drivers. A comparison of the mean scores of the two groups indicated several moderate differences between the groups. The mean scores of the attributes "not annoying", "appropriate urgency level", "high acceptance" and "not too startling" were higher for developers than for drivers. The mean scores for the attributes "appropriate orienting response", "prepares the driver to respond", "clearly audible",

and “easy to understand” were almost identical for both groups. The mean score for the attribute “easy to distinguish” was slightly higher for drivers than for developers. Mann-Whitney U tests revealed significant differences between the two groups for the attributes “appropriate urgency level” ($U=503.5$, $z=2.05$, $p=.04$, two-tailed) and “not too startling” ($U=434.5$, $z=2.79$, $p=.01$, two-tailed). No other significant differences were found at the $\alpha = 0.05$ level. However, differences in the attributes “not annoying” ($U=549$, $z=1.57$, $p=.12$), “high acceptance” ($U=520$, $z=1.88$, $p=.06$) and “easy to distinguish” ($U=858$, $z=-1.71$, $p=.09$) may be considered to be indicative.

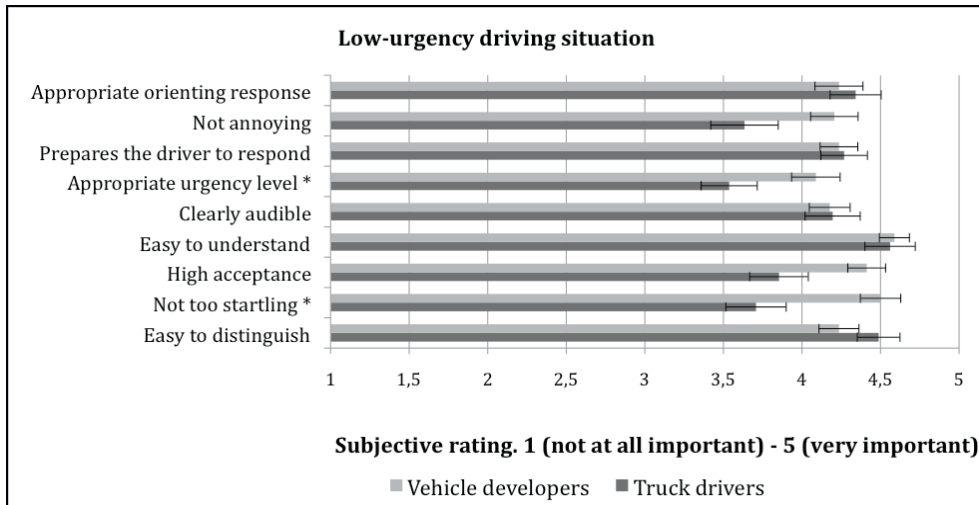


Figure 4 Mean ratings for the low-urgency driving situation. Error bars show standard errors. Two-tailed Mann-Whitney U tests were used to investigate differences between the two groups, * $p < 0.05$.

4 Discussion

The first research question under investigation in the present study was “which attributes of auditory warning signals do vehicle developers and commercial drivers consider important?” The results indicate that both system developers and drivers found most of the attributes included in the questionnaire to be important rather than unimportant in both the high-urgency and low-urgency driving situation. At first glance, the results look promising for the future of auditory warning signals in vehicles. If system developers, as well as drivers, are aware of the potential benefits and issues of using auditory signals, we might see more effective and tolerable auditory warnings in future ITSs.

Perhaps the most interesting result is that many developers rated the attribute “easy to understand” as very important in both the high-urgency and low-urgency driving situations. These results appear especially promising in light of the body of research that has reported how auditory warnings can be made more effective by making them easier to learn and interpret [1-4]. Furthermore, implementing informative auditory warnings in vehicles may potentially reduce visual load and allow drivers to stay more focused on the road in demanding situations. However, this particular result is also interesting considering that most auditory warnings used in in-vehicle systems today are very simple, abstract sounds. The sounds are abstract in the sense that they do not represent the danger, which in turn makes them challenging to learn and interpret. Possible reasons for the current state of auditory warnings might be that system developers do not have the methods, expertise or resources

available to find easily understood sounds. A few sets of guidelines to finding sounds that are easily associated with alarming functions have been published [23], and some developers may find guidance for their work in those guidelines. Another possible explanation could be that many in-vehicle warning systems do not have the technical capabilities to store and play complex sounds such as auditory icons or speech. Audio requirements should be considered earlier in the system design phase, allowing designers to prepare them not only for advanced visual content but also for more complex auditory signals.

Many of the developers (41%) indicated that it is unimportant whether high-urgency warnings are annoying to drivers. Previous research has shown that sounds designed to sound more urgent have a tendency to become more annoying [1,10,20]. Some degree of “annoying potential” is probably unavoidable for urgent warnings if they are to be effective. However, the level of induced annoyance should not be considered unimportant. Instead, developers should concentrate on finding sounds that are effective, while trying to keep annoyance within reasonable levels. Increased annoyance is a potential negative consequence of urgent sounds, but research has indicated that acoustic properties that affect urgency can have various effects on annoyance [10]. Making warnings implemented in vehicle interfaces easier to learn and interpret could also make them less annoying [3].

12 % of the developers rated that they consider whether the high-urgency sound is too startling to be “not at all important”. At the same time, the attribute “clearly audible” received the highest mean rating of the nine attributes (the developers who considered startling responses unimportant all considered it very important that the sound is clearly audible). It is inevitably important that a warning is audible. However, applying the “better safe than sorry” approach in warning design, i.e., prioritising the audibility while neglecting the startling effects may be a risky strategy. Not only may loud and startling sounds negatively impact system acceptance, the involuntary response could potentially negatively affect a driver’s ability to respond appropriately to an urgent situation.

The second research question under investigation in the present study was “Are there differences in the developers’ opinions regarding warning signals of different levels of urgency?” The results show that there were statistically significant differences between the high-urgency and low-urgency driving situations for seven of the nine investigated warning attributes. In a high-urgency situation, developers may find it especially important that the warning triggers an appropriate orienting response, that it prepares the driver to respond, that it is clearly audible, and that it is easy to distinguish from other sounds in the environment. In contrast, in a low-urgency situation, developers may be more concerned that the warning is not annoying to drivers, that it has an appropriate urgency level, that the driver accepts it, and that it is not too startling. It should be noted that the observed differences between the two situations were small or moderate, except for the attributes “not annoying” and “not too startling”. The developers rated these two attributes to be considerably less important in the high-urgency situation than in the low-urgency situation.

The third question that was under investigation in the present study was “Are there differences between the opinions of vehicle developers and those of professional drivers?” A comparison between the developer and driver ratings revealed a number of differences between the two groups’ opinions. In the high-urgency situation, the drivers rated the attribute “not annoying” as significantly more important than the developers did. The drivers may have ranked this attribute more highly because they recognise annoying warnings as potentially more disturbing in an urgent and demanding driving situation. A comparison of the mean ratings in the low-urgency situation revealed two significant differences between the groups. The attributes “appropriate urgency level” and “not too startling” were scored more highly by the developers than by the drivers. The attributes “high acceptance” and “not annoying” did not differ significantly between the two groups, but the

differences in these two attributes may still be considered indicative (p -values = 0.06 - 0.12, two-tailed). Interestingly, it seems like the developers considered the attributes related to a driver's mental state (annoyance, startling response) to be more important than did the drivers in the low-urgency situation. It is possible that the two groups judged the situation differently. The observed differences in the opinions of the developers and the drivers suggest that vehicle developers should consider involving experienced drivers in the process of designing auditory warnings. While developers probably have more experience in interface design, experienced drivers may contribute valuable situation-specific information.

Finally, both drivers and developers found many of the investigated warning attributes to be very important in both the high-urgency and low-urgency situations. However, developers should also be aware that the importance of each individual attribute could vary significantly from system to system. Driver environments are complex, and every driver interface system is unique. It is challenging to predict exactly how drivers will respond to a signal implemented in a unique environment. For instance, even though informative auditory warnings may be very effective in many systems and situations, a very simple auditory cue may actually be more appropriate. Fung et al. [24], for instance, conducted a simulation study to investigate the effectiveness of various auditory signals in a collision warning system. They concluded that a simple "beep" led to faster response times than no warning at all, but the response time to a speech message did not differ significantly from that in the no-warning situation. Thus, even though the attributes of warning signals may be highly important, the effectiveness of each auditory warning signal should be evaluated in its unique environment.

One potential criticism of the present study is that all vehicle developers and some of the drivers were employees of the company Scania CV AB in Sweden. The results may not be valid for all vehicle developers and professional drivers. More studies should be carried out with other companies and in other countries to verify the results of the present investigation. Also, the developers that participated were not necessarily working with sound design. However, they were working in related areas and could potentially be involved in projects and decisions regarding auditory warnings and warning functions.

6 Acknowledgements

Scania CV AB and The Swedish Information and Communication Technology Research (Swedish ICT) financed this work. Special thanks to Håkan Alm at Luleå University of Technology, and Robert Friberg and Anna Sirkka at Scania CV AB for support and inspiration.

7 References

- [1] McKeown, D.: 'Candidates for within-vehicle auditory displays', Proc. of Int. Conf. on Auditory Display 2005, Limerick, Ireland, 2005
- [2] Beltz, S.M., Robinson, G.S., and Casali, J.G.: 'A new class of auditory warning signals for complex systems: auditory icons', *Human Factors*, 1999, 41, (4), pp. 608-618
- [3] Fagerlön, J., and Alm, H.: 'Auditory signs to support traffic awareness', *IET Intelligent Transport Systems*, 2010, 4, (4), pp. 262-269
- [4] Graham, R.: 'Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application', *Ergonomics*, 1999, 42, (9), pp. 1233-1248
- [5] Ho, C., and Spence, C.: 'Assessing the effectiveness of various auditory cues in capturing a driver's visual attention', *Journal of Experimental Psychology: Applied*, 2005, 11, (3), pp. 157-174

- [6] Shelton, J.T., Elliot, E.M., Eaves, S.E., & Exner, A.L. (2009). The distracting effects of a ringing cell phone: An investigation of the laboratory and classroom setting. *Journal of Environmental Psychology*, 29, pp. 513-521
- [7] Cowan, N.: 'Attention and Memory. An integrated framework' (Oxford University Press, 1995)
- [8] Edworthy, J., Loxley, S., and Dennis, I.: 'Improving Auditory Warning Design: Relationship between Warning Sound Parameters and Perceived Urgency', *Human Factors*, 1991, 33, (2), pp. 205-231
- [9] Hellier, E.J., Edworthy, J., and Dennis, I.: 'Improving auditory warning design: quantifying and predicting the effects of different warning parameters on perceived urgency', *Human Factors*, 1993, 35, (4), pp. 693-706
- [10] Marshall, D.C., Lee, J.D., and Albert Austria, P.: 'Alerts for in-vehicle information systems: annoyance, urgency and appropriateness', *Human Factors*, 2007, 49, (1), pp. 145-157
- [11] Guillaume, A., Drake, C., Rivenez, M., Pellieux, L., Chastres, V.: 'Perception of urgency and alarm design', *Proc. of Int. Conf. on Auditory Display 2002*, Kyoto, Japan, 2002
- [12] Burt, J.L., Bartolome, D.S., Burdette, D.W., and Comstoc, J.R.: 'A psychophysiological evaluation of the perceived urgency of warning signals', *Ergonomics*, 1995, 38, (11), pp. 2327-2340
- [13] Wiese, E.E., and Lee, J.D.: 'Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance', *Ergonomics*, 2004, 47, (9), pp. 965-986
- [14] Västfjäll, D., Larsson, P., Genell, A., Sköld, A. and Kleiner, M.: 'A neuropsychological theory of sound design: Implications for auditory icon in vehicles. Proc. of the 2nd ISCA/DEGA Tutorial and Research Workshop on Perceptual Quality of Systems, Berlin, Germany, 2006.
- [15] Wickens, C.D., and Hollands, J.G.: 'Engineering Psychology and Human Performance', (Prentice Hall, 1999, 3rd edn.)
- [16] Staal, M.A.: 'Stress, Cognition, and Human Performance: A literature review and Conceptual Framework' (Ames Research Center, 2004)
- [17] Kowalski-Trakofler, K.M., Vaught, C., and Scharf, T.: 'Judgment and decision making under stress: an overview for emergency managers', *Int. Journal of Emergency Management*, 2003, 1, (3), pp. 278-289
- [18] Sköld, A.: 'Integrative Analyses of Perception and Reaction to Information and Warning Sounds in Vehicles', PhD thesis, Chalmers University of Technology, Sweden, 2008
- [19] Tajadura-Jiménez, A., Väljamäe, A., Kitagawa, N., and Västfjäll, D.: 'Affective multimodal displays: Acoustic spectra modulates perception of auditory-tactile signals. Proc. of ICAD 08, Paris, France, 2008
- [20] Tan, A.K., and Lerner, N.D.: 'Multiple attribute evaluation of auditory warning signals for in-vehicle crash avoidance systems', National Highway Traffic Safety Administration – Office of Crash Avoidance Research, Washington DC, USA, 1995
- [21] Spanias, A., Painter, T., and Venkratraman, A.: 'Audio signal processing and coding' (John Wiley & Sons, Inc, 2007)
- [22] Lerner, N.D, Kotwal, B.M., Lyons, R.D., and Gardner-Bonneau, D.J.: 'Preliminary human factor guidelines for crash avoidance warning devices', National Highway Traffic Safety Administration, Washington, DC, USA, Report no. HS 808 342, 1996
- [23] Ulfvengren, P.: 'Design of Natural Warning Sounds in Human-Machine Systems', PhD thesis, Royal institute of technology, Sweden, 2003
- [24] Fung, C.P., Chang, S.H., Hwang, J.R., Hsu, C.C., Chou, W.J., and Chang, K.K.: 'The study on the influence of auditory warning systems on driving performance using a driving simulator', Institute of Transportation, Taiwan, Paper no. 07-0170, 2007

