

# DISTRACTING EFFECTS OF AUDITORY WARNINGS ON EXPERIENCED DRIVERS

*Johan Fagerlönn*

Interactive Institute  
Sonic Studio  
Acusticum 4, 94128 Piteå, Sweden  
[johan.fagerlonn@tii.se](mailto:johan.fagerlonn@tii.se)

## ABSTRACT

A range of In-Vehicle Information Systems are currently developed and implemented in trucks to warn drivers about road dangers and vehicle failures. Systems often make use of conventional repetitive auditory warnings to catch attention. In a critical driving situation it might be tempting to use signals that express very high levels of urgency. However, previous studies have shown that more urgent alerts can have a negative impact on the listeners' affective state. A simulator experiment was conducted to examine how urgent warnings could impact the affective state of experienced truck drivers, and their response performance to an unpredictable situation. As predicted, the more urgent warning was rated more annoying and startling. The drivers who received an urgent warning braked significantly harder to the unpredictable event (a bus pulling out in front of the truck). The drivers also tended to brake later after the urgent warning, but no significant effect on response time or time to collision was found. A concluding recommendation for future research is to investigate distracting effects of urgent auditory warnings on less experienced drivers.

## 1. INTRODUCTION

A number of authors have reported that auditory cues could facilitate drivers in dangerous situations [1-4]. Sound can be perceived at any time, and regardless where the driver has visual focus. Thus, auditory cues may be especially appropriate in urgent situations that require attention.

As the number of In-Vehicle Information Systems (IVIS) increase – so does the number of auditory alerts and warnings. Therefore, it is becoming increasingly important to investigate the potentially negative effects that warning signals can have on drivers. The research presented in this article focuses on how urgent auditory warnings can negatively impact experienced drivers affective state, and ability to detect and respond to new information in the traffic scene.

Appropriate “urgency mapping” between warnings and events could guide drivers attention and help them prioritize better. A body of research has shown that manipulation of acoustical properties can impact the perceived urgency of a warning [5-9]. Edworthy et al. [5], for instance, identified a number of parameters such as pitch, harmonic series, speed and pitch range that had a consistent effect on urgency.

However, the perceived urgency of a sound may not solely depend on acoustical properties. Guillaume et al. [10] showed that the predictions by Edworthy et al. [5] were not completely

accurate when applied to real alarms from military aircrafts. Burt et al. [11] reported that even though participants were able to rank “sonic urgency” before an experiment, they were not able to do so after the experiment when sounds had been mapped to situations. In conclusion, it is established that both spectral and temporal aspects of a warning signal can raise urgency. However, perceived urgency may also depend on other associations and learned mappings.

Acoustical parameters that affect rated urgency might speed up reaction time (RT). Haas and Edworthy [8] found that higher pitch, signal level and inter-pulse interval (time elapsed from the end of the offset of one pulse to the beginning of the onset of the next) increased perceived urgency. They also reported that increased level and pitch decreased RT in a simple reaction task. Haas and Casali [7] reported that higher signal level and shorter time between bursts raised rated urgency, and increased signal level decreased RT in a simple reaction task. Jaśkowski et al. [12] also reported that increased signal level resulted in a faster RT. Suied et al. [13] showed that shorter inter-onset interval raised perceived urgency and decreased RT in a simple reaction task. Edworthy et al. [14] found that envelope shape, harmonic structure, pulse-pulse interval, rhythm, average pitch, pitch range and pitch contour) affected RT in a simple reaction task.

Previous studies have shown that parameters that affect urgency could impact perceived annoyance. Tan and Lerner [15], for instance, evaluated alerts for a collision warning system and reported that signals perceived as louder were rated more annoying. Wiese and Lee [16] reported that warnings designed to sound urgent tended to speed drivers' accelerator release. But they were also rated more annoying. Wiese and Lee recommended that designers should consider an annoyance trade-off in addition to urgency mapping. Marshall et al. [9] identified a number of parameters (harmonic series, pulse duration, inter-pulse interval, alert onset and offset, burst duty cycle, inter-burst period and sound type) that affected both perceived urgency and annoyance. They concluded that annoyance is an important factor to consider in system design, especially when designing alerts for less critical situations. But the various parameters affected urgency and annoyance differently. Thus, the assumption that parameters that increase urgency increase annoyance in a corresponding way may not be completely valid.

Designing sounds that are not annoying is important for several reasons. Unpleasant alarm tones have been found to be a common reason why operators disable the sound of communicating systems [17]. Also, unpleasant signals have been found to impact both drivers' mental workload and

performance. Wiese and Lee [16] found a correlation between rated annoyance of auditory warnings and perceived workload (NASA-TXL) when drivers performed a simulated driving task. Baldwin [3] examined semantic and acoustical properties of verbal warning signals and reported that signals of intermediate urgency decreased crash risk during simulated driving. The high-urgency warning used in the experiment was considered to be very annoying and did not reduce crash risk.

We still know relatively little about how acoustical parameters that affect perceived urgency could impact drivers' ability to take in and process information. Inherent urgency may motivate the driver to focus on some particular area of the road scene or interface. However, urgency represents an increased level of threat, which may require an immediate physiological and psychological reaction (higher arousal). One sign of high arousal levels is increased attentional narrowing [18, 19]. A certain degree of alertness and focus is probably appropriate in an urgent situation. But severe attentional narrowing may not be appropriate in complex and eventful situations that require the driver to share attention between several ongoing events. Thus, a better understanding of how warning signals can impact drivers attention have important implications for IVIS design.

Based on the previous studies of acoustical properties and annoyance there are reasons to believe that urgent signals can impact drivers affective state. A number of studies have found that characteristics in sound that raise annoyance and urgency also increases perceived arousal. Tajadura et al. [20] investigated alerts from an emotional perspective and found that higher pitch increased perceived arousal. Västfjäll et al. [21] reported that perceived annoyance of aircraft noise correlated with perceived arousal.

The potential effect of arousal on drivers' selective attention was demonstrated by Chapman and Underwood [22]. An experiment was conducted to investigate drivers' visual behavior when watching traffic situations with different levels of danger. More dangerous (arousing) situations "were characterised by a narrowing of visual search, shown by an increase in fixation durations, a decrease in saccade angular distances, and a reduction in the variance of fixation locations".

The present experiment was designed to investigate how an urgent warning can impact the affective state of experienced drivers, but also their ability to detect and respond to less predictable events in the traffic scene. Based on previous research it was predicted that a more urgent warning would be considered more annoying and startling. It was also predicted that a more urgent warning would result in a delayed response to an unpredictable traffic event.

## 2. METHOD

24 professional truck drivers between the ages of 23 and 70 years ( $M=43.3$ ,  $SD=13.1$ ) participated in the experiment. Their truck driving experience ranged from 1 to 46 years ( $M=21.0$ ,  $SD=12.9$ ) and their annual driving ranged between 15000 and 150000 km ( $M=90218$ ,  $SD=3838$ ). All drivers had normal or corrected-to-normal vision and self-reported normal hearing. They all gave their informed written consent to participate in the study.

### 2.1. Apparatus

The experiment was conducted in the VTI Driving Simulator III at the Swedish National Road and Transport Research Institute [23]. This high-end simulator has an advanced motion system that enables lateral or longitudinal acceleration forces up to 0.8g. A vibration table is implemented under the vehicle cab to simulate different road conditions. The traffic scene is presented on three main screens covering 120 degrees of the driver's visual field. These projections are accompanied by three rear mirrors covering the rear view. Taken together, the VTI Driving Simulator III is capable of producing a realistic driving experience in a highly controlled setting.

### 2.2. Stimuli

Two auditory warning signals were created prior to the experiment. Both signals were designed to warn drivers about vulnerable road users (pedestrians) standing close to the roadside. They started with a 1000 ms verbal message, "pedestrians", presented in Swedish by a female voice. The message was followed by one of two sets of tone bursts that lasted for 1500 ms. Both spectral and temporal parameters of the burst sets were manipulated to make them different in terms of perceived urgency. Pitch and harmonic series have been suggested to affect perceived urgency [5, 6, 8, 9, 11]. The low-urgency warning had a fundamental frequency of 179 Hz (G3). The high-urgency warning consisted of a cluster of tones (B4, C5, D5, C6, B6), which formed a disharmonic sound with higher frequency components. The speed of a signal has also been suggested to affect urgency [5, 7-9]. The low-urgency warning contained 2 bursts with a 300 ms inter-pulse interval. The high-urgency sound had 8 bursts with 10 ms inter-pulse intervals. Shorter amplitude onset and offset have been found to increase perceived urgency [5, 9]. Amplitude onset and offset times for the low-urgency warning was 300 ms and 450 ms. Onset and offset times for the high-urgency warning was 25 ms and 210 ms. Haas and Casali [7] and Haas and Edworthy [8] reported that higher loudness increased rated urgency. Warnings were calibrated to approximately 80 dB(A) and 85 dB(A), which prevented them from being masked by other sounds in the environment. The background noise was calibrated to be approximately 64 dB(A) at the drivers' position at 50/km speed. Both warnings were presented in the spatial position of the pedestrians in a 6.0 channel speaker setup (Anthony Gallo Acoustics Inc, CA, USA).

### 2.3. Evaluation of auditory signals

A study was conducted to test whether the two signals would be perceived differently in terms of perceived urgency and affective reaction. 18 volunteer subjects (16 males and 2 females) participated. Their ages ranged from 20 to 56 years ( $M=32.4$ ,  $SD=8.4$ ). The sounds were presented in counterbalanced order in a pair of KOSS UR5 headphones (Koss Corporation, WI, USA). The participants listened to background noise recorded inside a mini van for one minute. After 20 seconds the first warning was triggered. The participants were then required to rate perceived urgency, startling effect and annoyance using rating scales ranging from 1 (not at all) to 7 (very much). The participants also rated their

affective reactions using the Self-Assessment Manikin (SAM) [24]. After another 30 seconds the second warning was triggered. Results of the ratings are presented in Table 1. Two-tailed paired t-tests were used to test for significance between distributions. The urgent warning produced significantly higher ratings in all parameters at the 0.01 alpha level.

	High urgency	Low urgency	p-value
Urgency, 1-7	5.9 (1.2)	4.0 (1.6)	<0.01
Startling, 1-7	4.6 (2.0)	2.6 (1.7)	<0.01
Annoyance, 1-7	5.5 (1.2)	3.0 (1.8)	<0.01
Arousal, 1-5	3.8 (1.1)	2.5 (0.9)	<0.01
Valence, 1-5	3.8 (0.9)	2.6 (0.6)	<0.01

Table 1: Mean ratings for the two auditory warnings. Standard deviations are presented in parentheses.

#### 2.4. Traffic situations

Two critical situations were designed for the experiment. In one situation (bus), illustrated in Figure 1, the driver received a warning about pedestrians standing near the roadside. A bus was parked ahead of the crowd. Just as the truck passed the pedestrians the bus started to pull out and the driver was required to brake immediately to avoid a collision.

In the other traffic situation (car), the truck was heading an intersection with a small crowd of people standing near a cross walk. The driver received a warning about the pedestrians. Just as the truck entered the intersection, a passenger vehicle approached at high speed from the right and the driver were required to brake to avoid a collision.

Pilot trials were conducted with four drivers to identify any issues regarding the structure and timing of the critical events. A problem found was that the drivers tended to stop for the pedestrians. It was therefore decided to move the pedestrians further away from the road. Another issue was regarding the timing of the critical event in the car situation. It was problematic to get the car in a position so that drivers would spot it and take action to avoid a collision. The timing was adjusted in the pilot trials and it was decided to use the situation in the experiment.



Figure 1: Traffic situation with pedestrians and a parked bus. Drivers received a warning about the pedestrians standing to the right. Moments later the bus pulled out in front of the truck.

#### 2.5. Procedure

The experiment was conducted using a within-subjects design. Critical situations with warning signals were presented in counterbalanced order. At arrival, the drivers were introduced to the VTI Driving Simulator III and the driving task. They were informed that the vehicle was equipped with a system capable to warn them about potential road dangers. Each participant drove one practice scenario that lasted for about 8 minutes, and then the main driving scenario that lasted for 25-30 minutes. In total, each driver passed 18 intersections and 8 buses during the main driving scenario. Each critical event occurred three times – one time directly after a high-urgency warning, once after a low-urgency warning, and once without a warning. Both types of warning also occurred one time without a following critical situation. The drivers were told not to exceed the speed limit of 50 km/h. Brake response time, time to collision (TTC), brake force and subjective ratings of annoyance and startling effect defined the main dependent variables.

Directly after the trial, participants completed a questionnaire containing statements about the critical situations, the driving task and the warning signals. The drivers were required to rate perceived annoyance and startling effect using rating scales ranging from 1 (not at all) to 7 (very much). A loosely structured interview was also conducted to collect complementary driver input. At this point the experimenter revealed the purpose of the experiment and the drivers were allowed to talk freely about any issues experienced during the trials. The experimenter especially paid attention to comments about the auditory signals and how drivers focused their attention in the dangerous situations.

### 3. RESULTS

Results are based on data from 24 participants. Complete brake response data was collected in the bus situation. Mean time between the drivers received a warning and the bus pulling out was 2807 ms (SD=957). Unfortunately, there was severe loss of data in the car situation. The reason was an issue with timing, which prevented many participants to brake for the car. Thus, all data from that situation was excluded from analysis.

#### 3.1. Affective reactions

Table 2 shows mean values for the ratings of perceived annoyance and startling effect. As predicted, the drivers rated the urgent signal as significantly more annoying and startling. 2 drivers rated the low-urgency warning as being more annoying, and only 1 driver rated the non-urgent warning as being more startling than the high-urgency warning. A two-tailed paired t-test revealed significant differences between the sounds both in terms of rated annoyance ( $t(23)=2.94$ ,  $p=0.007$ ) and startling effect ( $t(23)=3.14$ ,  $p=0.005$ ).

<b>Annoying (1-7)</b>	<b>Mean</b>	<b>Median</b>	<b>SD</b>
High urgency	4.42	5	1.84
Low urgency	3.42	3	1.56
<b>Startling (1-7)</b>			
High urgency	3.71	4	1.88
Low urgency	2.71	3	1.60

Table 2: Subjective ratings of annoyance and startling effect.

### 3.2. Brake response

Table 3 shows mean response time, time to collision and brake force. All drivers successfully avoided a collision. Brake force was measured in terms of maximum brake pressure level. Two-tailed paired t-tests failed to show any significant effects between treatments in any of the dependent variables at the 5% alpha level. A moderate correlation was found for the variables brake force and TTC (Spearman’s rank order correlation,  $r=-0.54, p<0.01$ ), and brake force and brake response time ( $r=0.59, p<0.01$ ).

<b>Response time (ms)</b>	<b>Mean</b>	<b>Median</b>	<b>SD</b>
High urgency	1441	1410	381
Low urgency	1352	1290	284
<b>Time to collision (ms)</b>			
High urgency	2000	1900	490
Low urgency	2088	2100	411
<b>Brake force (bar)</b>			
High urgency	4.5	4.05	2.33
Low urgency	3.76	3.75	1.79

Table 3: Descriptive statistics for the driving parameters.

### 3.3. Analysis of first situations

Several drivers stated that they radically changed their expectations about threatening situations after the first critical situation. Also, the drivers responded considerably faster in the second situation ( $M=1233, SD=269$ ) compared to the first situation ( $M=1559, SD=320$ ). A two-tailed paired t-test showed that the difference was significant ( $t(23)=3.63, p=0.0013$ ). It was therefore decided to examine the results from the first situations in more detail. In this analysis 12 drivers who received an urgent warning were compared with 12 drivers who received a low-urgency warning. Mean time between drivers receiving a warning and the bus pulling out was 2564 ms ( $SD=769$ ) in the first situation. Mean brake response time, time to collision and brake force are presented in Table 4.

<b>Response time (ms)</b>	<b>Mean</b>	<b>Median</b>	<b>SD</b>
High urgency	1637	1610	370
Low urgency	1482	1520	251
<b>Time to collision (ms)</b>			
High urgency	1900	1850	381
Low urgency	2133	2050	369
<b>Brake force (bar)</b>			
High urgency	6.06	7.15	2.05
Low urgency	4.23	4.15	1.74

Table 4: Driving parameters in the first situation.

### 3.3.1. Brake response

Mean brake response time was longer after the high-urgency signal compared to the low-urgency signal. The mean difference between groups was 155 ms. However, an independent samples t-test returned no significant difference between the distributions at the 0.05 alpha level. Mean time to collision was also shorter, but the difference was not significant.

Most drivers who received an urgent warning braked harder than drivers who received a non-urgent warning. 58 % of the drivers who received an urgent warning reached brake pressure levels close to highest possible brake pressure. Normal distribution of data was not assumed. Both a two-tailed Mann-Whitney U-test, and a two-tailed independent samples t-test returned a significant difference in maximum brake pressure between the distributions ( $U=113, n_1=n_2=12, p<0.05$ ) ( $t(22)=2.43, p=0.024$ ).

## 4. DISCUSSION

The purpose of this experiment was to investigate how urgent auditory warning signals may impact experienced drivers affective state and ability to respond to other, more unpredictable events in the road scene.

One could argue that the most important property of a warning is that it will be detected by the driver and contribute to a fast response. Previous studies have shown that more urgent signal could speed response time in a simple reaction tasks [7, 8, 13, 14]. Wiese and Lee [16] investigated the effects of an urgent warning during simulated driving and reported that increased burst density of a collision warning speeded accelerator release.

However, annoying auditory signals could undermine acceptance, and have been suggested to be a common reason why operators turn of system alerts [17]. Wiese and Lee [16] suggested an annoyance trade-off when designing warning signals for in-vehicle use. The results obtained in the present experiment indicate that warning signals presented in a truck cabin could impact affective state differently. As predicted, the high-urgency warning was rated more annoying and startling compared to low-urgency warning. These results were not at all surprising and they are in line with previous findings suggesting that acoustic properties can affect rated urgency, annoyance and arousal [9, 15, 16, 20]. But most previous studies have been conducted with ordinary car drivers or not in a driving context. The present study was conducted in a high-end truck simulator with highly trained truck drivers. On the basis of the result from this and previous studies we suggests that truck manufacturers should not only consider alarm efficiency, but also annoyance potential when designing and implementing auditory warnings.

Mean scores of annoyance were almost identical to the results in the pre-study for the low-urgency warning. But the high-urgency warning was rated considerable less annoying by the professional truck drivers. A two-tailed t-test reveals that the difference is significant ( $p<0.05$ ). There are several possible explanations to this effect. One could be that professional drivers are used to handle critical driving situations, and simply felt less affected by the urgent sound. Other contributing factors could be that the subjects in the pre-study only listened to the

sounds one time, and that the signals were not mapped to any situations. The professional truck drivers listened to them 3 times, and the sounds were mapped to specific traffic situations. Previous findings suggest that perceived urgency of warnings can change considerably when they have been mapped to situations, even though the listener is told to ignore any associations and just focus on the sound [11]. Also, in the interview one driver stated that it was hard to remember the sounds being different. The ratings were performed after completing the 25-30 minutes driving task and the participants may not have been able to provide precise ratings of their affective state at this time. In future studies it may be more appropriate to let drivers rate their affective state directly after the critical situations.

Analysis of response performance in first situations showed that the drivers who received a high-urgency warning braked significantly harder than drivers who received the low-urgency warning. Previous experiments have suggested that increased arousal [12] and the "stimulus-response compatibility" [25] could lead to more forceful reactions. The moderate correlation found between response time and brake force suggests that drivers compensated for late responses by braking harder.

Drivers who received the high-urgency warning also tended to brake later compared to drivers who received the low-urgency warning. But there were large differences between drivers, and the differences did not reach statistical significance. But even so, there are reasons to consider more studies examining distracting effects of urgent alerts on drivers. Today, car manufacturers are developing and implementing new technology to assist ordinary car drivers in dangerous and eventful situations. Experienced drivers are probably more used with critical and demanding situations than are less experienced drivers. Chapman and Underwood [22] found that novice drivers showed longer fixation durations than experienced drivers in critical traffic situations, indicating that they are less able to share attention appropriately in these situations. Future studies should examine the effects of urgent warning signals on less experienced drivers.

Previous studies have emphasized the use of early warnings instead of late warnings in a driving context. Lee et al. [4] found that early warnings helped distracted drivers more effectively than did late warnings. In a second experiment they showed that early warnings resulted in a safety benefit by reducing the time required for drivers to release the accelerator. Early and more comfortable warnings that inform the driver about important states and ongoing events could be an especially interesting alternative to alarming and annoying signals. If an extremely fast response time is important, it is probably better to consider overtaking systems such as automatic brake systems.

The length of the trials prevented any investigation of long-term effects and habituation of the signals. No considerable effect on brake response behavior was found after the first situation, indicating that response performance for experienced drivers will not be negatively affected by "sonic urgency" when critical situations are expected.

## 5. CONCLUSIONS

The results of the experiment suggest that acoustical parameters that increase urgency can impact experienced drivers' affective

state in demanding traffic situations. Urgent signals could potentially also impact drivers' responses to unpredictable events in the traffic scene. These results have implications for system design, especially for systems designed to warn and inform drivers in very complex and eventful situations. Previous authors have suggested developers should consider an annoyance trade-off when implementing auditory warnings in vehicles. The results of this study imply that it may be a good idea to also consider a tradeoff between perceived urgency and contextual complexity. A recommendation for future research is to investigate distracting effects of auditory warning signals on less experienced drivers.

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