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The Effect of an Emotionalizing Sound Design on the Driver's Choice of Headway in a Driving Simulator

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Abstract: This study investigates the impact of emotionalizing sound design on driving behaviour, focusing on the effect of an acoustic stimulus that varies from positive to negative/threatening based on the vehicle's time headway (THW). Our primary goal was to explore how this sound influences driving durations within specific THW ranges and the mean THW itself. The experiment utilized a control group and a within-participant setting across simulated driving scenarios. The statistical analysis showed mixed results. While participants in the control group setup did not demonstrate significant reductions in the durations of driving in lower THW ranges, a modest but significant increase in mean THW was observed when the emotionalizing sound was active. However, within-participant comparisons showed both a significant decrease in the duration of driving at lower THWs and an increase in mean THW when the negative stimulus was active, suggesting the stimulus' effectiveness in promoting safer driving habits. These findings highlight the potential of emotionalizing sound design to influence driver behaviour towards maintaining safer distances, although the impact appears to diminish at higher THW ranges. Future research should further investigate the characteristics of sounds that effectively modify driving behaviour, aiming for broader applications in traffic safety.

Keywords: vehicle interior noise; active sound design; electric vehicle; psychoacoustics; emotional stimulus; traffic safety; time headway; driving simulator

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1. Introduction

As traffic safety continues to be a significant concern globally, it is crucial to explore new methods to enhance driving safety. This paper begins with a definition of time headway (THW) and its relevance in traffic safety. Further, the limitations of current safety systems like emergency braking and the reticent adoption of proactive distance maintenance technologies are discussed. The focus then shifts to defining an emotionalizing sound design as a possibility to improve traffic safety: By altering emotional states through specific sound characteristics, drivers could be influenced to maintain adequate safety distances. Prior studies on the effects of auditory stimuli on driving behaviour are reviewed to establish the foundational context for the current study, which tests the impact of emotionally charged sounds on driving safety, particularly in regard to the THW.

Time headway (THW) is a critical metric for gauging the risk of particular traffic scenarios. It calculates the time gap from when the leading vehicle's front end passes a fixed point on the road to when the following vehicle's front end crosses the same point, thereby offering an estimation of situation criticality [1]. The THW is calculated as stated in Formula (1):

$$Time\ Headway = \frac{Headway\ [m]}{Velocity\ \left[\frac{m}{s}\right]} \tag{1}$$

Driving in insufficient THW accounts for 16% of traffic accidents in Germany [2] and is a significant contributor to traffic fatalities [3]. The legislation and suggestions in regard to safe and unsafe or even sanctioned safety distances or THW differ greatly, even when focusing only on western Europe [4]. An often-suggested rule of thumb for a safe safety distance seems to be at least 2 s of THW. In Germany, the guideline of the Federal Motor Transport Authority suggests keeping a distance of half the current velocity in meters [5], which translates to a THW of 1.8 s. At higher speeds, such as those on highways which this study targets, having a THW less than half of this rule could result in being registered as a traffic offender in Germany. Repeated offenses of maintaining a THW under 0.9 s can lead to a (temporary) revocation of the driver's license.

To tackle the problem of traffic accidents, a variety of emergency braking systems have been developed to act in dire situations [6]. Nonetheless, such systems do not guarantee the maintenance of safe following distances. Although there are systems designed to help drivers maintain appropriate distances from the vehicle ahead, they have not seen widespread use, nor are they compulsory, like emergency braking systems [7]. The difficulty with these systems is that their operational characteristics are quite similar to those of standard warning systems, which may lead drivers to ignore important signals due to the overwhelming amount of information presented to them [8]. A different strategy might be realized by utilizing an emotionalizing sound design, which involves a proactive approach to active sound design with the objective of modifying a driver's emotional state during specific driving scenarios, thereby affecting their driving behaviour. This alteration in emotional state is caused by changing the emotional character of the active sound design by changing its harmonic composition or sound characteristics. Auditory elements like sounds and music are characterized by various attributes, such as pitch, timbre, tonality, volume, and rhythm. These attributes correspond to acoustic and psychoacoustic properties, with terms like harmonics, sharpness, roughness, and fluctuation strength explaining the timbre of a sound, while periodicity or impulsiveness describe its rhythm [9,10]. Research has shown that modifications, e.g., changes in volume [11,12], frequency composition [13], auditory signals, and non-driving related sounds such as music [14], can alter the perception of speed while driving. Brodsky's study revealed that music influences both physiological and behavioural responses during simulated driving, finding that faster-paced music led to increases in simulated driving speed and speed estimations, as well as a rise in virtual traffic violations, including running red lights [15].

When examining auditory stimuli's effects on drivers, it is important to consider the emotional impacts. Kleinginna et al. define emotion as "a complex set of interactions among subjective and objective factors, mediated by neural/hormonal systems, which can (a) give rise to affective experiences such as feelings of arousal, pleasure/displeasure (valence); (b) generate cognitive processes such as emotionally relevant perceptual effects, appraisals, labelling processes; (c) activate widespread physiological adjustments to the arousing conditions; and (d) lead to behaviour that is often, but not always, expressive, goal-directed, and adaptive." [16] (p. 355). Valence is a fundamental aspect of emotions that describes whether a stimulus is perceived as attractive or repulsive. Positive valence indicates that something is perceived as good or appealing. On the other hand, negative valence suggests that something is seen as bad or unappealing. In general, people gravitate towards experiences that are perceived as pleasant (positive valence) and steer away from unpleasant ones (negative valence) [17]. The desire to approach or avoid becomes more pronounced with increased arousal levels in positive or negative valence states [18].

Music and auditory stimuli have been shown to be able to induce different emotions depending on their auditory characteristics. The emotional response elicited by certain intervals in simultaneously played tones varies with the frequency difference between the tones [19]. Musical chords, which are groups of three or more tones, can evoke different emotions; for instance, chords with dissonant intervals, such as diminished chords, tend to be perceived as more negative compared to the less dissonant major chords [20]. Higher pitches or chords usually correspond to positive emotions, whereas lower ones are associated with negative emotions [21]. In general, musical elements like the harmonic composition of sounds, rhythmic percussive sounds, as well as hissing and whooshing noises can shape the overall emotional experience of an individual in regards to emotions with negative valence like fear, sadness, or joy [9,22,23].

Current research in active sound design focuses on enhancing the positivity of synthetic sounds or fostering positive emotions through the sounds produced by electric vehicles [24,25]. However, states of anxiety and fear have been observed to affect driving behaviours, including speed and acceleration patterns [26]. Moreover, exposure to negative emotional auditory stimuli has been found to decrease braking reaction times in both risky and non-risky scenarios [27] and to correlate with a reduced inclination towards risk-taking [28]. These findings suggest that an emotionalizing sound design could play a significant role in providing feedback on the driving context and affecting safety-related behaviours, such as risk-taking and chosen THW.

Many modern vehicles are equipped with sensors that continuously monitor the distance to other vehicles [7]. By leveraging data from these sensors along with vehicle parameters, an active sound design system could modify the sound's mood (from positive to negative) based on the vehicle's current THW. This approach aims to influence the driver's emotional state, potentially altering their driving behaviour [29].

In an initial study by Petersen et al., 16 designed sounds were evaluated for their emotional impact on participants. The findings indicated that sounds causing a sense of threat correlated with higher fluctuation strength and impulsiveness, whereas calmness was associated with lower fluctuation and impulsiveness and higher tonality [30]. In a second study, participants were exposed to video materials of car-following scenarios, each randomly accompanied by sounds designed to evoke either positive emotions, such as light-heartedness, or negative emotions, such as a sense of threat. The results showed a significant increase in the estimation of shown safety distances in videos combined with sounds invoking positive emotions vs. sounds invoking negative. We found that two of the three negative sounds significantly increased the chance of participants viewing safety distances as too short by two to three times compared to the most positive sound. Moreover, the presence of threatening sounds amplified participants' desired increases in the shown safety distances in the scenarios presented [31]. These results highlight the influence of an emotionalizing sound design on drivers' safety distance assessments, underscoring their potential role in traffic safety and the importance of considering an emotionalizing sound design within the automotive context.

In this paper, we use a dynamic emotionalizing sound design based on the effective positive and negative sounds of the previous video-based study in a driving simulator experiment to investigate its effect on driving behaviour in regard to safety distance. To have an effect of improving traffic safety, the emotionalizing sound design should have an effect at lower THW ranges to improve safety distance. To quantify the effect on the safety distance, we decided on the duration of driving in lower THW ranges as well as the mean THW in different THW ranges. Based on the state of research, the suggested safe THW by the German Federal Motor Transport Authority [5], and its relevance for a driving study conducted in Germany, we propose the following hypotheses:

Hypothesis 1. *The duration of driving in THW ranges <1.8 s is decreased when driving exposed to a negative emotionalizing acoustic stimulus controlled by the THW compared to driving without the stimulus.*

Hypothesis 2. *The driven mean THW is increased in THW ranges <1.8 s when driving exposed to a negative emotionalizing acoustic stimulus controlled by the THW compared to driving without the negative stimulus.*

We test these hypotheses first in a control group setup when looking only at the first of two drives where participants are randomly assigned to drive with or without the emotionalizing stimulus. In a second analysis, we compare both of the two drives of the participants in regards to differences in driving behaviour while driving with and without the stimulus in randomised order.

2. Materials and Methods

2.1. Materials

The validation environment utilized for the driving tasks is a static driving simulator developed by the Institute for Human and Industrial Engineering (IFAB) at Karlsruhe Institute of Technology (KIT). This simulator employs the proprietary SILAB simulation software by the Würzburg Institute for Traffic Sciences GmbH and is modelled after a compact car class automatic vehicle. The simulator has a speedometer display, a centre console display, and simulated mirrors with digital displays. Its primary visual setup consists of a monoscopic curved screen and three projectors, offering a 180-degree field of view. Simulation scenarios are created using the SILAB 7.0® software [32], which enables the control of vehicle dynamics, computer-controlled road users, interactions with other road users, and environmental factors and outputs vehicle-related sounds realistically and flexibly. Furthermore, the software facilitates comprehensive monitoring of various parameters throughout the simulation, including the recording of vehicle and traffic data. Moreover, it supports the integration of external hardware or software components, such as the sound generator used in this study, through dedicated software interfaces [33]. A picture of the driving simulator can be seen in Figure 1.

Figure 1. Driving simulator setup at the Institute of Human and Industrial Engineering (IFAB) at KIT.

The driving tasks conducted with each participant consisted of two introductory driving tasks and two driving tasks to evaluate the efficacy of the emotionalizing sound design on the chosen headway. The first introductory task was around 6 min long and consisted of acceleration and breaking sub-scenarios to get accustomed to longitudinal dynamics and behaviour of the vehicle model and driving simulator. It further entailed slalom sub-scenarios to get accustomed to the lateral dynamics and behaviour of the vehicle model and the driving simulator. The second introductory consisted of following a road through a rural area for about 8 min. It contained narrower and wider curves that necessitated the adjustment of the current velocity. The second introductory drive was used to enhance the feeling of driving in the driving simulator and to reach a level where participants stated they could drive as they would in real life. Further, these introductory tasks were necessary to get the participants acquainted with the initially often strange sensation of driving in a static full-screen driving simulator and also to identify participants suffering from simulator sickness.

The driving scenarios to evaluate the efficacy of the emotionalizing sound design on the chosen headway are based on a realistic-looking highway drive with two driving lanes. It is based on a demo scenario from the SILAB driving simulator that was populated with different traffic sub-scenarios. The driving scenario was around 11 km long. To ensure minimal differences between two driving tests—one with and one without the emotionalizing stimulus—while preventing immediate recognition of task similarity, we made subtle changes: the first turn after starting at a highway parking bay was altered to be either left or right, and the vehicles at the parking bay were varied. This setup balanced comparability with reduced risk of participants recognizing the tasks as identical, as they were focused on driving. The driving scenarios are not virtual replicas of existing road infrastructures in Germany but rather inspired by the general look and feel of German highways. The scenarios forced participants to interact with vehicles ahead at their chosen headway, while overtaking was impossible due to the traffic situation. Vehicles initiating these sub-scenarios were introduced out of sight but consistently positioned, ensuring uniform driving experiences across different speeds. The sub-scenarios can be categorised into four different groups: following overtakes, a following scenario through a construction site, a vehicle swerving onto the left driving lane, and a following scenario through a traffic jam. An overview of the driving tasks, as well as the sub-scenarios, can be seen in Figure 2.

The car-following overtakes in sub-scenarios 1,3,5,6, and 7 consisted of one vehicle on the left lane and two or three vehicles on the right lane that are being overtaken by the vehicle on the left lane. The vehicle on the left lane was driving 129 km/h in areas with a restriction of 130 km/h and 140 km/h in unrestricted areas. The overtaking vehicle on the left lane was around 20% faster than the vehicles on the right lane. The following scenario in the construction site (sub-scenario 2) consisted of following a vehicle on the left lane driving 59 km/h (restriction was 60 km/h) for about 400 m. The vehicle decelerated calmly from 100 km/h before the construction site and accelerated to 100 km/h after the construction site before making the way free on the left lane. In the swerving vehicle sub-scenario 4, a vehicle drives on the right lane in a column of vehicles approaching slower construction vehicles (50 km/h) while accelerating slowly to 140 km/h. The participant approaches this scenario on the left lane at around 90–100 km/h. When the participant is 100 m away from the swerving vehicle, the vehicle changes smoothly from right to left lane in around 3 s using the indicator. The participant then needs to break towards a slower accelerating vehicle and follow it for 500 m. The last sub-scenarios, 8 and 9, relate to a traffic jam that occurs after a long left-hand curve. When approached by the participant, the vehicles smoothly decelerate from 54 km/h to 18 km/h, holding that speed for 30 m, and then accelerating smoothly to 150 km/h (unrestricted area). The participant needs to break towards decelerating vehicles and then follow them at their chosen headway till they reach 150 km/h after accelerating and move to the right lane.

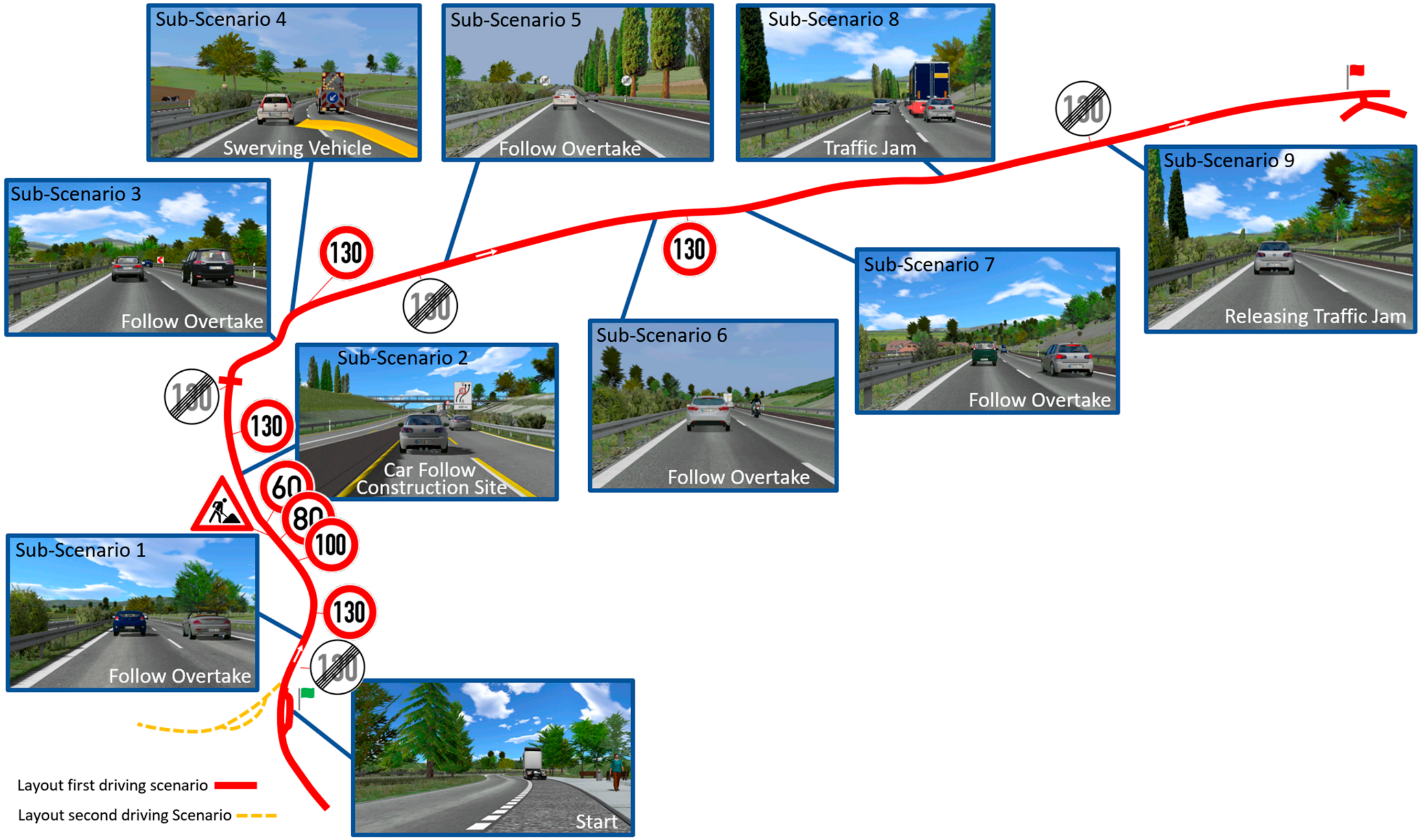


Figure 2. Layouts 1 and 2 of the two driving scenarios for the driving tasks with the traffic sub-scenarios and their respective speed limits.

2.2. Acoustic Stimulus

For the sound design, our self-developed sound generator created in Native Instruments Reaktor 6 is used (Reaktor 6, version 6.5.0, Native Instruments GmbH, Berlin, Germany). It was developed to change its sound and, thus, the emotional character drastically based on real-time vehicle and traffic conditions [29,31]. The outputs used from the driving simulator were the calculated engine RPM, the engine torque, and the longitudinal distance [34]. In [34], they are discussed, and it is shown how they are translated and transmitted to the sound generator by a Python software interface.

The acoustical stimuli consisted of two different sound designs. For the driving tasks without the emotionalizing stimulus, we only use a positive-sounding active sound design that does not change with an undershoot of a certain THW. The positive sound we used was the positive sound of [31], being based on a major chord and consisting of only sine waves. The sound is changed in pitch analogous to the engine RPM. It increases in volume and very slightly in added overtones (due to a slight distortion) and minimal roughness-inducing amplitude modulation based on the current engine torque. The active sound design for the driving task with emotionalizing stimulus consists of the same positive active sound described before but additionally changes continuously based on the current THW. The sound stays positive until the THW is smaller than 1.8 s. The sound design then changes continuously towards becoming more negative and threatening. For the emotionalizing stimuli, we used the sounds of the previous study [31], which showed to have an emotionalizing effect and were already created with our real-time sound generator. In Figure 3, the continuous change from the harmonic sound on the left to the fully changed stimulus on the right is displayed.

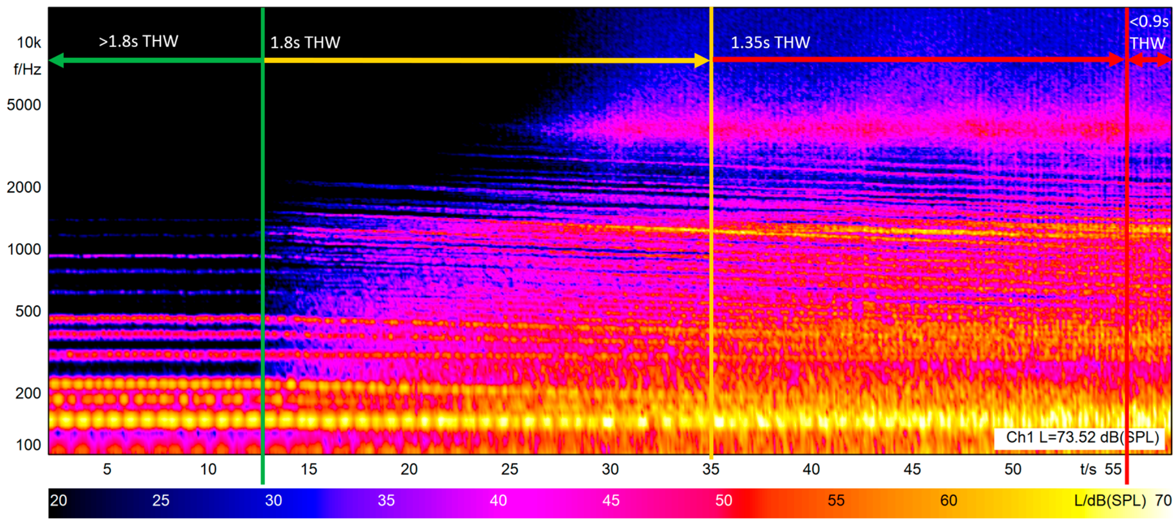


Figure 3. Spectrogram of the emotionalizing sound design continuously shifting from the normal positive sound design at THW > 1.8 s to the threatening sound design at THW < 0.9 s over 60 s.

From 1.8 s THW to 1.35 s THW, the active sound design changes continuously to the first recreated sound (Sound 4) of the previous study [31]. It was based on a diminished chord and contained additional overtones due to an additional Shepard-Partial stacking higher frequency component on top of each of the chord notes. Further, it contains a metallic hissing sound produced by a white noise processed by a delay effect set to a very low feedback time (10.2 ms) that increases in volume with a decreasing THW. For the change from a major to a diminished chord, we do not change the fundamental tone but only the major third to a minor third and the fifth to a fourth. From 1.35 s THW to 0.9 s THW the active sound design changes further continuously to another sound (Sound 5) of the previous study [31]. It is fundamentally the same sound as the sound at 1.35 s, but the chord is further altered by changing the minor third to a minor second and the fourth to a minor third, resulting in a very disharmonic sound. Furthermore, the psychoacoustic impulsiveness and fluctuation strength are continuously increasing via a rising amplitude modulation with a modulation frequency of around 2 Hz. The envelope of the amplitude modulation transitions continuously from a sinus wave to a square waveform. The chord notes, as well as the impulsiveness and fluctuation strength, are gradually increased to the maximum setting at 0.9 s THW or lower, resulting in a hammering tone when reaching 0.9 s THW. In Figure 4, we see the curve progression of the psychoacoustic Loudness, Sharpness, Fluctuation Strength, and Impulsiveness (Hearing Model) for the gradual change between 1.8 s THW and 0.9 s THW for both the left and right stereo channels. It was focused on these four psychoacoustic metrics, as these represent the fundamental changes that are applied to the sound.

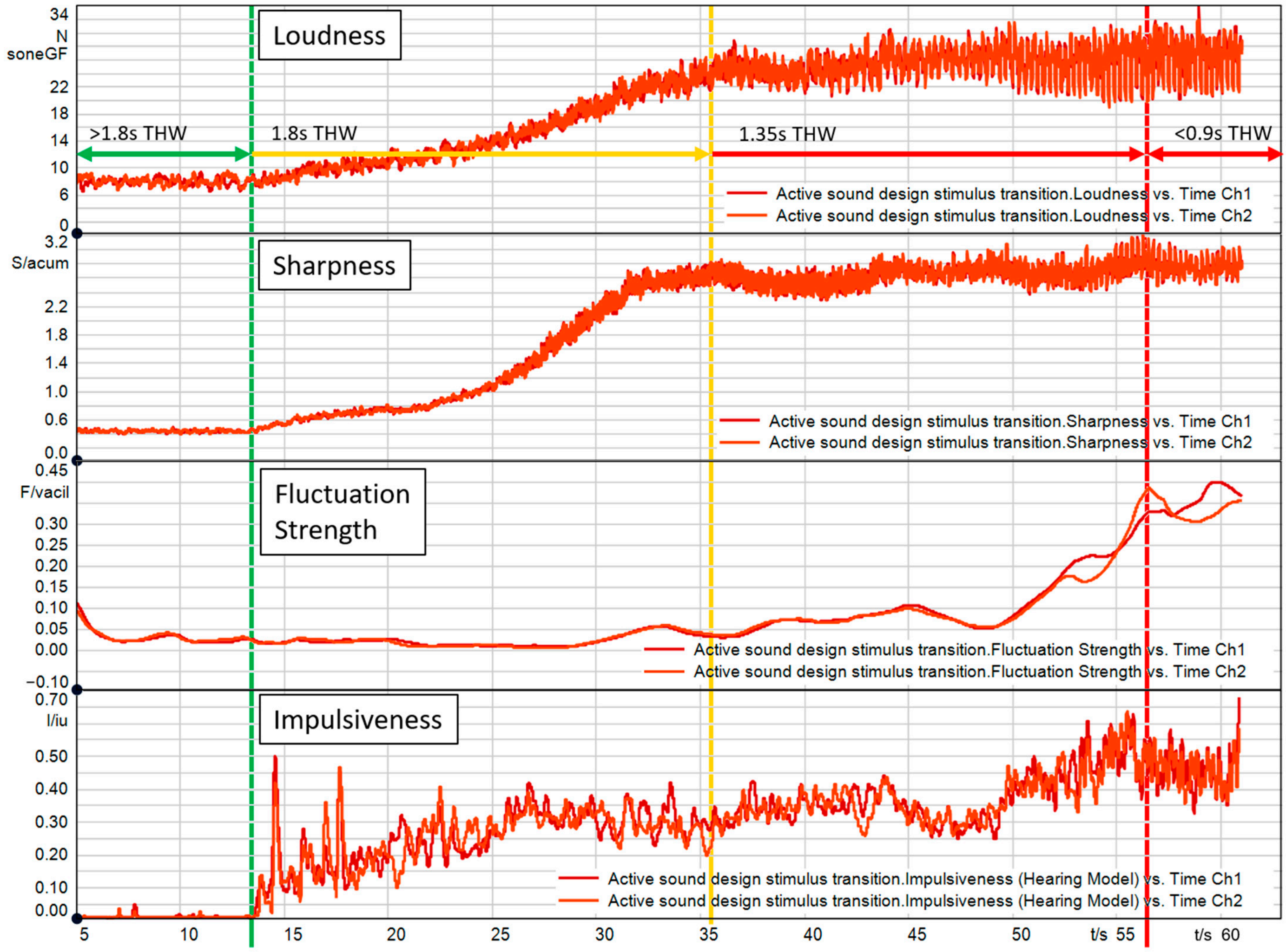


Figure 4. Curve progression of the psychoacoustic Loudness, Sharpness, Fluctuation Strength, and Impulsiveness (Hearing Model) of both stereo channels for the sound design continuously shifting from the normal positive sound design at THW > 1.8 s to the threatening sound design at THW < 0.9 s over 60 s.

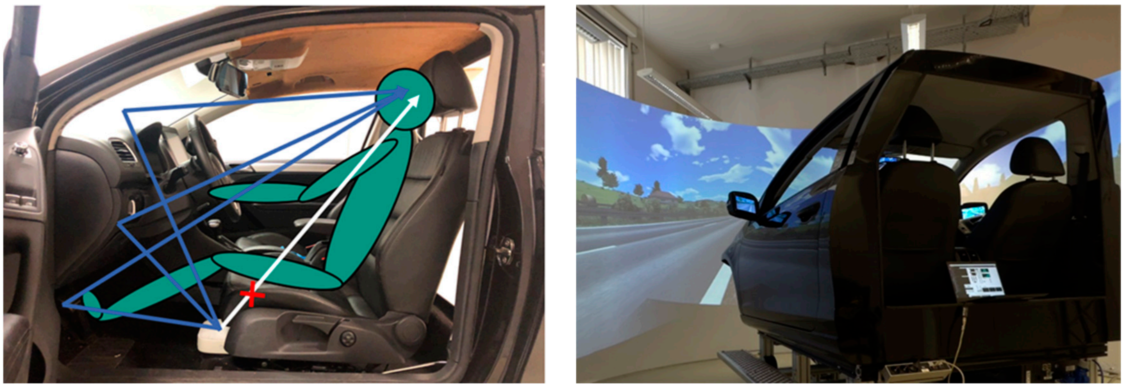
It can be seen that there is a rise in the loudness over the change of sound with a lowering THW. This stems primarily from the additional frequency content due to the added Shepard-Partial, as well as the additional metal hissing sound aspect, which can also be seen in the Sharpness diagram. Furthermore, in the area after 1.35 s THW, we can see an increase in the fluctuation in the loudness due to the increase in amplitude modulation. The increase in fluctuation strength, as well as impulsiveness in the sound, can also be seen in their respective diagrams. Interestingly, the more sinus wave-based amplitude modulation at around 1.2 s THW seems to not increase the fluctuation strength significantly compared to the pulse wave amplitude modulation at 0.9 s THW. Also, the fade-in of the additional Shepard-Partial causes very high levels of impulsiveness, even though the level increases rather slowly with decreasing THW.

2.3. Integration of the Sound into the Vehicle Cabin

For the integration of the sound design into the simulator's environment, it is essential for the sound design to be clearly audible and seamlessly incorporated within the vehicle's cabin. The process of integrating the sound was already described in [34], but for a better understanding, the necessary details are summarized here. Typically, the SILAB simulator utilizes the car's original Hi-Fi system speakers to emit its sound simulations. These include the internal synthesis of an Internal Combustion Engine (ICE) vehicle's sound, consisting of an ICE engine noise, along with the reproduction of rolling and primarily wind noises that intensify with speed. Moreover, sounds from the external environment, such as other cars and trucks passing by, are also emitted through these speakers. Initial trials revealed that the internal sound of the vehicle in the simulator, when played through the Hi-Fi system alongside other sounds, lacked a realistic quality of originating from the actual vehicle rather than just being played back through speakers near the driver's head. This perception grew stronger when the internal ICE sound was substituted with the more abstract and futuristic-sounding active emotionalizing sound design developed for the study. To address this, an additional speaker was installed in the driving cabin to enhance the naturalness of the sound emanating from the vehicle itself. The setup consisted of a laptop running the sound generator and transmitting the sound via a USB audio interface (Fireface UC, RME, Haimhausen, Germany) to a smaller speaker (Helsinki, VIFA, Heldensborg, Denmark). The speaker has a rather neutral and even sound output across the entire frequency range and is particularly detailed in the mid-frequency region crucial for the sound design. It also delivers a strong performance at very low frequencies (around 58 Hz), which were felt as slight vibrations in the driver's seat within the simulator. Various locations were explored and subjectively assessed for effectiveness. The different positions were assessed by a consortium of five scientific employees of the vehicle acoustics department of the institute, as well as two external acoustic engineers. The most convincing location identified was beneath the driver's seat, protruding 7 cm forward, where the direct transfer path of sound waves to the driver was obstructed by the seat, relying instead on indirect paths through reflections from the vehicle's interior. This configuration makes the source of the sound challenging to pinpoint, unlike the direct paths from the Hi-Fi speakers, creating a multi-directional audio effect at the vehicle's front, mimicking the acoustic experience in a real vehicle. The setup and examples of these sound paths are illustrated in Figure 5a [34].

With an immersive, subjectively optimized position being found, the last step is an appropriate volume level necessary for the sound playback. This is determined by two major factors. The first one is a realistic level of playback compared to the sound levels in a real vehicle, as described in [34]. Also, the played-back sound should not be masked by other noises existing in the driving simulator, like the aforementioned wind noise, or external noises, like the simulator hardware. The last one could be especially problematic since the driving simulator does not have any windows apart from the front windshield and no sound insulation in the back of the driver cabin, as seen in Figure 5a [34].

In order to determine the appropriate settings for sound playback, binaural measurements were performed using an artificial head (Manakin Mk1 Cortex, dBSonic, Eseneler, Istanbul, Türkiye) that simulates the spatial constraints of an individual seated in the simulator and listening with their own ears. Figures 6 and 7 illustrate the data from measurements across six varied sound setups [34].



(**a**) (**b**)

Figure 5. (**a**) Transfer paths of the sound design from speaker to driver ear. The crossed out white arrow represents the interrupted direct transfer path and the blue arrows represent exemplary transfer paths for the reflected sound waves. (**b**) Open back side of the vehicle cabin in the driving simulator.

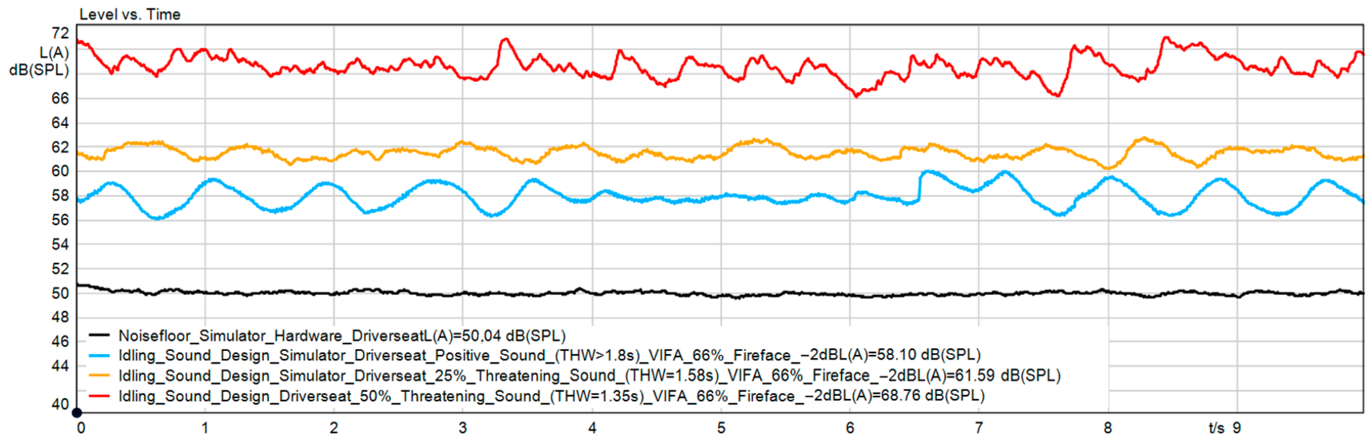


Figure 6. Sound pressure level vs. time for artificial head measurement inside the vehicle cabin for the noise floor with running simulator hardware and with three different settings for the activated sound design.

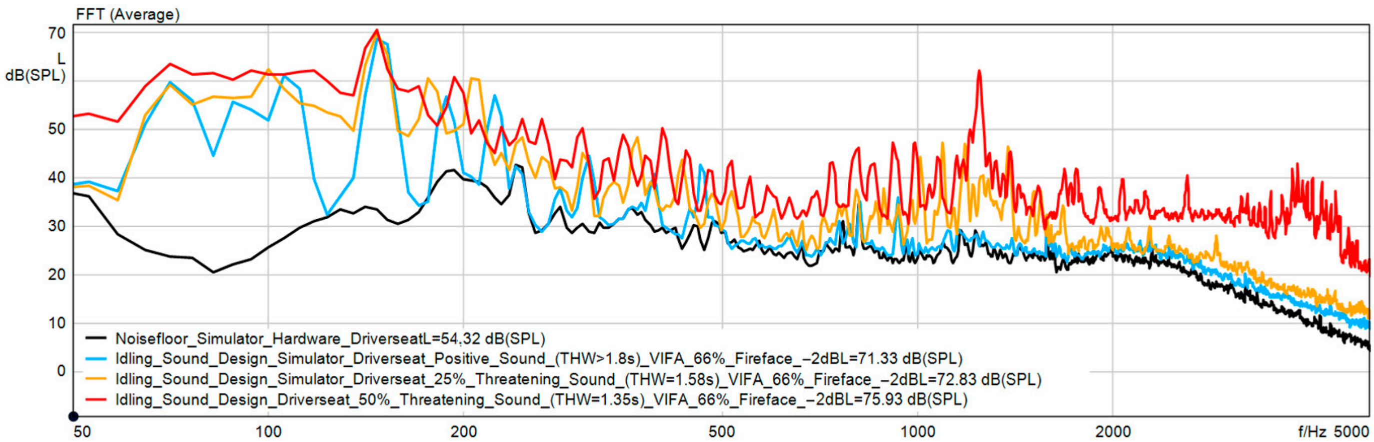


Figure 7. Spectrum for artificial head measurement inside the vehicle cabin for the noise floor with running simulator hardware and with three different settings for the activated sound design.

Measurements of the noise floor with the running simulator hardware were taken with the sound design deactivated. Additionally, the final volume levels for the activated sound design were measured while the car was idling, including the standard positive sound as well as the more intimidating versions with 25% (1.58 s THW) and 50% (1.35 s THW) threatening stimuli. Higher intensity levels are not presented as they only escalate in volume [34].

The target for the sound pressure level inside the simulator vehicle cabin is around 58 dB(A) which fits the common level for the noise floor in electric vehicles [34]. The noise floor in the running simulator is around 8 dB lower, approximately 50 dB(A), which provides ample margin for the sound design to be clearly heard at around 58 dB(A). Figure 7 demonstrates that the distinct frequency peaks of the positive sound design at 160 Hz, 190 Hz, 215 Hz, 320 Hz, 380 Hz, and 415 Hz exceed the noise floor by at least 10 dB(A). The final sound settings were at the Fireface UC at −2 dB amplification and 66% volume on the Helsinki speaker.

To assess how effectively the sound design distinguishes itself from the wind, rolling, and traffic noises in the driving simulator, an additional measurement was carried out. This involved a drive at 140 km/h through a densely populated scenario section. The sound pressure levels over time for this drive, without sound design, with the positive sound, and with a 25% (1.58 s THW) threatening stimulus, are illustrated in Figure 8 [34].

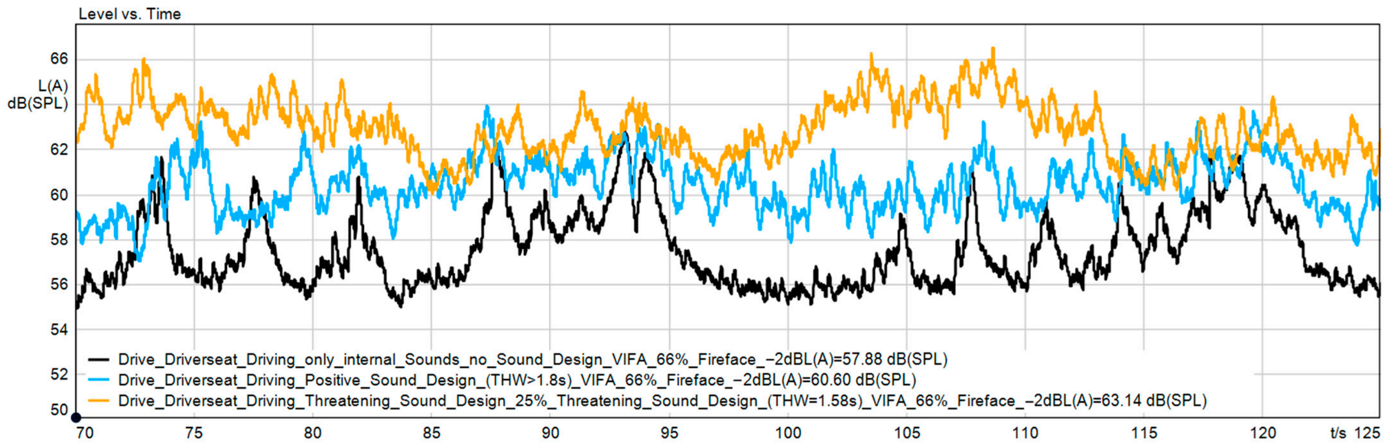


Figure 8. Sound pressure level vs. time for artificial head measurement inside the vehicle cabin, driving 140 km/h along a crowded scenario part. Three different settings: no active sound design, positive active sound design, and 25% threatening sound design.

Beyond the peaks of elevated levels, while overtaking other participants, the level curves when the sound design is active consistently remain well above the combined wind and traffic noise from the measurements without sound design on. Subjectively, the blend of wind noise, traffic noise, and active sound design was perceived as adequately realistic and immersive by the consortium [34].

2.4. Participants

A total of 54 people participated in the study. Moreover, 5 people had to abort their participation due to motion sickness. Further, 6 people were exempt from the analysis due to the following reasons: Three participants stated they drove not like they would in real life. Two participants misread the instructions and acted drastically differently in one of the drives based on consequential assumptions. One participant never fell below a safety distance that would activate the stimulus in either of the two drives, leading to no usable data. This leaves 43 participants. The sample was of rather younger age. A total of 9 participants are between 18 and 25 years old, 15 participants between 26 and 35, 14 participants between 36 and 45, 1 participant between 46 and 55, 3 participants between 56 and 65, 1 participant 66 or older. The sample was predominantly male (Female: 11, Male: 31, Diverse: 1). All participants owned a driving license for approximately 16 years (Mean = 16.6, Median = 15, range: (1, 55)). Only 5 participants stated having an accident in the last 2 years. Most participants reported driving up to 6000 km per year (up to 6000 km: 19 participants; 6001 km–9000 km: 11 participants; 9001 km–12,000 km: 5 participants; 12,001 km–15,000 km: 5 participants; more than 15,000 km: 3 participants). The reported usual driving environments were in the city (30 participants), in rural areas (18 participants), and on the motorway (25 participants).

2.5. Methods

The experiment consisted of two different task categories: answering questionnaires and completing driving tasks in a driving simulator. The questionnaires were used to collect data about the sociodemographic data, driving experience, driving habits, and open questions about the subjective perception and effect of the sound or the sound stimulus. The open questions were as follows:

- In what situation did you notice this change in noise?
- How did you feel when the sound changed?

The driving tasks in the driving simulator were conducted to evaluate the efficacy of the sound stimulus on the chosen headway. A driving simulator was used because it offers a good relative and sometimes even absolute validity of the results depending on the setup of the driving simulator and the investigated effects or behaviour [35–37]. Further, they offer the repeatability and safety of potentially risky driving tasks that would not be achievable in real driving scenarios. In this experiment, the relevant factor to investigate was the chosen headway by the participants during the driving task. Baumberger et al. found that there was an offset in the ability to evaluate the distance to other traffic participants between real driving and driving in their driving simulator [38]. For the investigation of the effect of an emotionalizing sound design on the chosen headway, relative validity is sufficient because the goal is not to quantify the effect of such a sound design but rather to initially verify that there is a significant difference between and within drivers driving with and without the emotionalizing stimulus. The experiment setup was chosen to offer both a control group experiment when only focusing on the first drive of each participant in the analysis and a within-design experiment when comparing both drives in the analysis. The assignment of the scenario for the driving task, as well as the order of driving first with or without the stimulus, was randomized for all participants. But each participant drove both scenarios and both either with or without the emotionalizing stimulus. The scenario differed only in the parked cars at the start and whether the first curve of the track was left- or right-hand bend. In the initial briefing, the participants were only told that the experiment was about driving with an electrical vehicle inside a realistic driving simulator setting. They gave their written consent that the acquired data would be anonymously used in further research and publications. They were further instructed that they could end the experiment at any time and were briefed about the condition of simulator sickness. Afterward, the instructional driving tasks were performed. In the next step, the actual driving tasks for the evaluation of the efficacy of the emotionalizing sound design were performed. Before each of the driving tasks, the participants received the written instruction in German:

- Scenario 1/2:
- Task:
    - You are on your way to Knoblach. You have an important appointment there. You are already running a little late, but you can still make it on time.
    - Drive as you would in real life.
- Information:
- Scenario: Motorway journey section 1 or 2
    - Vehicle: Electric vehicle with automatic transmission and an artificially generated vehicle interior noise (Active Sound Design)
- No sudden damage or technical problems can occur to the vehicle during the journey.

The point about being "a little late" was given to present some extrinsic motivation to not drive very slowly but increase the chances of people staying on the left lane and interacting with vehicles in front of them. Knoblach is not a real place, but one that was present in the modified demo used for the driving tasks. It acted as the goal for the 11 km driving task. The information that there is no sudden damage to the vehicle is possible was added so people would not come to the wrong conclusion that the sound changes are due to sudden damage to the vehicle. After the first drive, participants filled out the questionnaire about sociodemographic aspects as well as driving experience and driving habits (how many km per year and where they predominantly drive). During the driving tasks, the following parameters were recorded with a sampling frequency of 133 Hz: velocity [km/h], Time of measurement [m:s:ms], longitudinal distance (Headway) [m], Current Track Segment, Driven distance on current Segment [m] and Current Lane. The simulation measures the headway to the next vehicle on the same lane in front of the driven vehicle as long as it is closer than 500 m. It consequently is not productive to consider the whole drive for the comparison because the mean THW would be distorted by the very large values of headway driving in between the sub-scenarios where no interaction with a vehicle in front is taking place. To evaluate the effect of the emotionalizing sound design on traffic safety beyond the stated hypotheses, the recorded drive data were filtered by four different THW ranges:

- **THW < 4 s:** This headway range is chosen as a rather wide range. It is close enough that the vehicle in front ahead is clearly visible and considerations about the targeted headway should start to take place in the participant. This range could also be indicative of whether the emotionalizing stimulus has some sort of lasting effect above the direct effect while the stimulus is active (THW < 1.8 s)
- **THW < 1.8 s:** When undershooting 1.8 s, the normal active sound design starts to change into an emotionalizing sound design. This value was chosen because 1.8 s THW is suggested in Germany as a safe THW to drive in. This THW range distinguishes the drive with the emotionalizing stimulus and without in this experiment.
- **THW < 1.35 s:** At 1.35 s, the emotionalizing sound design changed to the diminished chord, and the metallic hissing is at maximum level, but the amplitude modulation causing the impulsiveness and fluctuation is still not present. This is the range in which the changes in sound are very much audible and should show an effect of the sound design if there is one.
- **THW < 0.9 s:** In this THW range, the emotionalizing sound design is at its maximum level in regards to inharmoniousness, impulsiveness, and fluctuation strength. Further, driving in this THW range is sanctioned in Germany as it is deemed unsafe to do so.

For the analysis of the efficacy of the emotionalizing sound design, the duration that the participants are driving in certain THW ranges, as well as the mean THW, are compared in two analysis setups. The first is a comparison based on the control group setting, where only the first of the total of two drives of all participants is considered. In this setting, the participants are grouped based on whether their first drive was conducted with the emotionalizing stimulus or without based on the randomized assignment. The group driving without the emotionalizing stimulus is the control group. For the analysis, the duration of driving in certain THW ranges and the mean THW while driving in the THW ranges are compared between the control group and the group driving with the emotionalizing stimulus. The duration gives us information on whether the emotionalizing sound design leads to a decrease in driving closer to other cars. The mean THW gives us an indication of whether there was a difference in the THW within the different THW ranges.

The second analysis setup is a within-participant comparison, where both drives (with and without the emotionalizing stimulus) of each participant are considered. Whether their second drive was with or without the stimulus depended, as described above, on the setup of their first drive. For this analysis setup, the duration of driving in a THW range and the mean THW in the different THW ranges are also compared.

For the within-participant analysis of the differences in mean THW, the data are further processed. The recorded drives are aligned by the track sections seen in Figure 3 to reduce the deviation over driving time between the two drives by one participant due to different velocities in the two recorded drives. To increase comparability between the two drives, only those parts of each of the drives were used where the participant drove on the same lane in both drives.

For the statistical analysis, we used the *Mann–Whitney U-Test* for independent measures and the pairwise *Wilcoxon Signed Rank Test* instead of Student's *t*-test. The statistical analysis was conducted in *R*. The THW data were not normally distributed, as assessed by Shapiro–Wilk's test ($p < 0.05$), and the sample size is only marginally larger than 30, so the *t*-test should not be used [39]. For the statistical analysis of the control group setting, the one-tailed *Wilcoxon Rank Sum Test* was used to find significant directed differences in the durations of the participants driving in the different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s), as well as the mean THW with and without the emotionalizing stimulus in only the first drive task. For the statistical analysis of the within-participant design setting, the one-tailed *pairwise Wilcoxon Signed Rank Test* for repeated measures was used to find significant directed differences in the duration within participants driving in the different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s), as well as the mean THW with and without the emotionalizing stimulus over the two driving tasks. Cohen's suggested r values of 0.1, 0.3, and 0.5, representing small, medium, and large effect sizes, respectively, were used to interpret the calculated statistical effect size of the difference in the duration of driving in the THW ranges as well as the mean THW based on [40].

3. Results

The results chapter contains the descriptive statistics and the statistical analysis of the effects of the emotionalizing sound design on driving behaviour as well as the perception and emotional effect of the sound design. First, the results for the control group setup will be displayed, and after that, the results for the within participant comparison.

3.1. Descriptive Statistics Based on the Time Headway in the Control Group Setup

For the descriptive statistics of the control group comparison, the durations in seconds the participants were driving in the four different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) for the drives with vs. without the stimulus are compared first. Figure 9 shows the boxplots for the duration of driving in the THW over the whole of the first drives of the participants. The thick line represents the median, and the dotted line is the mean.

Table 1 shows the means, the medians, and the standard deviation for the duration in seconds the participants were driving in the four different THW ranges for the first drive with or without the stimulus.

For the THW < 4 s and THW < 1.8 s, the mean and median are very close between the with and without stimulus drives. Based on the mean, a difference seems to appear at ranges below 1.35 s of THW. This is when the change in sound and, thus, the stimulus is clearly audible.

For the second comparison between people driving with or without the stimulus in the first drive, we compare the mean THW in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s). Figure 10 shows the boxplots for the mean THWs over the whole of the first drives of the participants. The number of samples for the THW ranges < 1.35 s and < 0.9 s is reduced due to participants not falling below these THW values while driving.

Table 2 shows the means, the medians, and the standard deviation over all the mean THWs in seconds the participants were driving in the four different time headway ranges for the first drive with or without the stimulus.

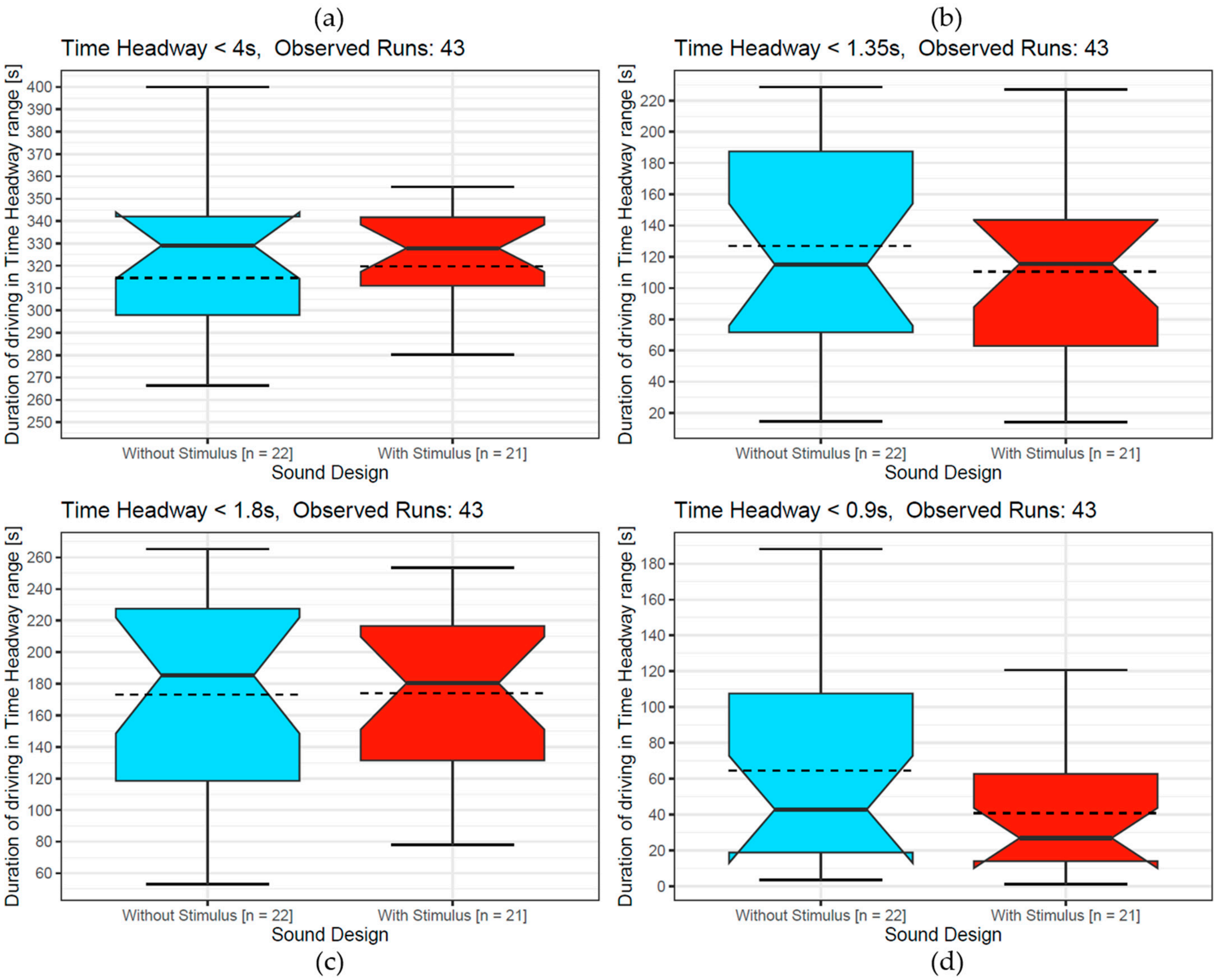


Figure 9. Box plots for the durations in seconds the participants were driving in the four different THW ranges (THW < 4 s (**a**), THW < 1.8 s (**b**), THW < 1.35 s (**c**), and THW < 0.9 s (**d**)) for the first drive of each participant either with or without the stimulus. The lower and upper borders of the box represent the 1st and 3rd quartiles, respectively. The whiskers represent 0.25–1.5 IQR/0.75 + IQR (interquartile range), and outliers are drawn interdependently.

Table 1. Mean, median, and standard deviation of the durations in seconds the participants were driving in the four different time headway ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) in the first drive either with or without the stimulus.

Duration of Driving in THW Range (s)		Mean	Median	Standard Deviation	n
THW < 4 s	Without Stimulus	314.6	329.1	49.8	22
	With Stimulus	319.8	327.9	28.3	21
THW < 1.8 s	Without Stimulus	173.2	185.2	68.5	22
	With Stimulus	174.0	180.4	51.8	21
THW < 1.35 s	Without Stimulus	127.0	115.0	68.9	22
	With Stimulus	110.5	115.6	57.4	21
THW < 0.9 s	Without Stimulus	64.6	42.9	57.3	22
	With Stimulus	40.9	26.9	35.1	21

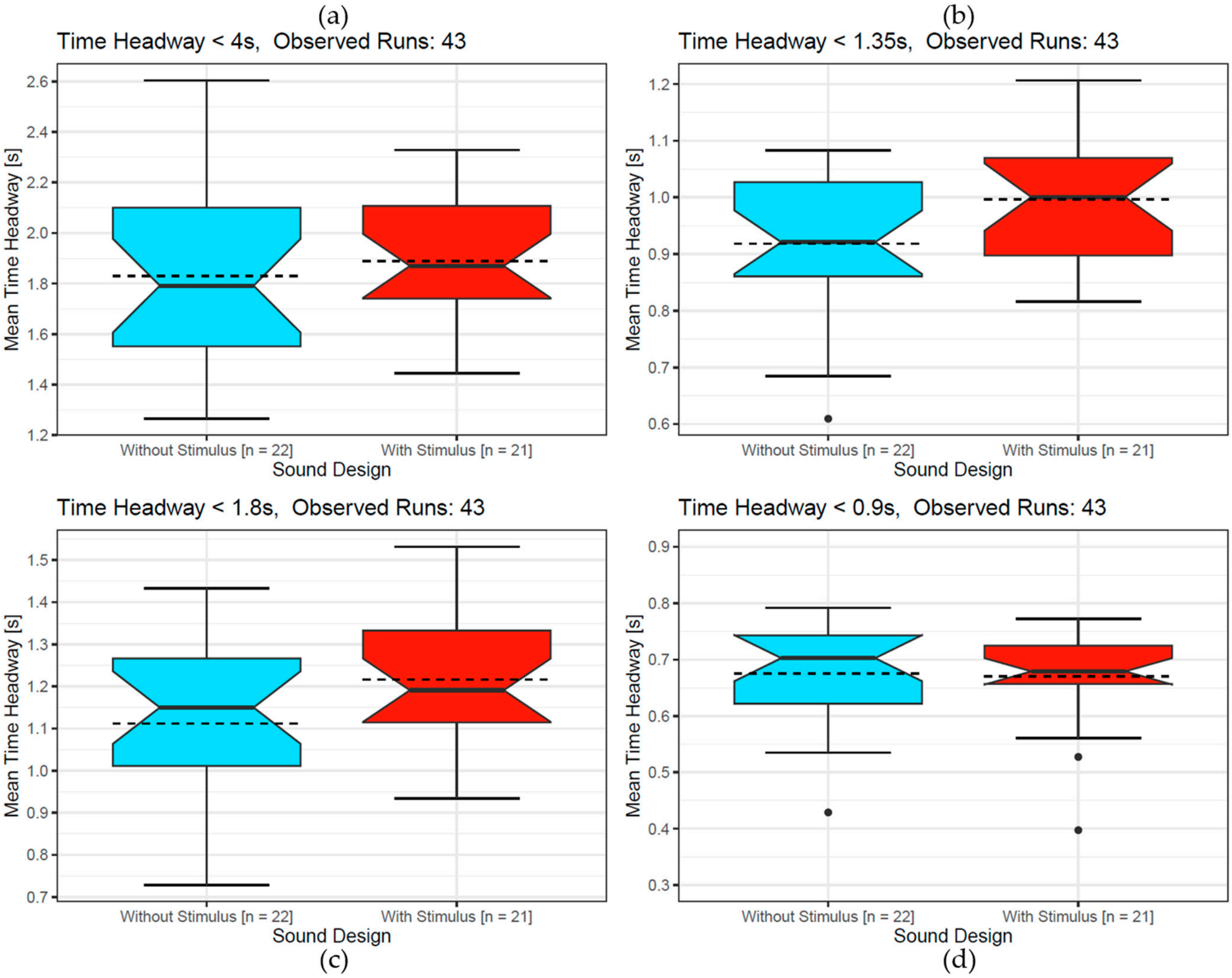


Figure 10. Box plots for the durations in seconds the participants were driving in the four different time headway ranges (THW < 4 s (**a**), THW < 1.8 s (**b**), THW < 1.35 s (**c**), and THW < 0.9 s (**d**)) for the first drive with or without the stimulus. The lower and upper borders of the box represent the 1st and 3rd quartiles, respectively. The whiskers represent 0.25–1.5 IQR/0.75 + IQR (interquartile range), and outliers are drawn interdependently.

Table 2. Mean, median, and standard deviation of the THW in seconds the participants were driving in the four different time headway ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) in the first drive either with or without the stimulus.

Mean THW in THW Range (s)		**Mean**	**Median**	**Standard Deviation**	**n**
THW < 4 s	Without Stimulus	1.83	1.79	0.37	22
	With Stimulus	1.89	1.87	0.25	21
THW < 1.8 s	Without Stimulus	1.11	1.15	0.19	22
	With Stimulus	1.22	1.19	0.15	21
THW < 1.35 s	Without Stimulus	0.92	0.92	0.13	22
	With Stimulus	1.00	1.00	0.11	21
THW < 0.9 s	Without Stimulus	0.68	0.70	0.09	22
	With Stimulus	0.67	0.68	0.09	21

For the THW < 4 s, THW < 1.8 s, and THW < 1.35 s ranges, the mean and median show an increase for the drives with the stimulus compared to drives without the stimulus. For the THW < 0.9 s, the mean and median are very close, indicating that either the full stimulus was less effective or that people driving so close were not influenced by the negative sound stimulus.

3.2. Statistical Analysis of the Effect on the Time Headway in the Control Group Setup

To test whether the emotionalizing sound design (stimulus) had an effect on the participants driving with the stimulus compared to the control group driving without it, a statistical analysis was conducted. The method chosen is the one-tailed Mann–Whitney U-Test for independent measures. For the first hypothesis, we test for a decrease in the duration driven in the THW ranges when the emotionalizing stimulus is active. For the second hypothesis, we test for an increase in the mean THW driven in the THW ranges when the emotionalizing stimulus is active. The one-tailed Mann–Whitney U-Test for independent measures was implemented in R (Version 4.3.1) using the R-function *wilcox.test* of R's native stats package. The method was chosen because it allows for a group-wise comparison of the increase or decrease in differences of at least ordinal dependent variables (durations of driving in THW range (s) or mean THWs (s)) based on a binary independent variable (with vs. without stimulus). The effect size was calculated from the Z-Value calculated by the *wilcox.test* function and the sample size. The results of the one-tailed Mann–Whitney U-Test testing for a decrease in duration driven in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) with stimulus are shown in Table 3.

Table 3. Results of one-tailed independent Mann–Whitney U-Test testing for a decrease in duration of driving in lower time headway ranges while driving with stimulus compared to a control group driving without the stimulus: mean differences, effect size, Z-values, exact significances, sample size with/without stimulus, standard deviation, standard error, and the upper confidence interval.

Mann–Whitney U-Test		**Comparison: Duration Driving in THW Range of First Drives of All Participants**						
THW Range	**Mean Difference**	**Effect Size**	**Z-Value**	***p***	**n per Stimulus**	**Standard Deviation**	**Standard Error**	**Conf. Interval (95%) Upper**
THW < 4 s	5.20	0.10	−0.68	0.50	22/21	40.77	12.44	−0.38
THW < 1.8 s	0.82	0.13	−0.86	0.39	22/21	60.92	18.59	−0.49
THW < 1.35 s	−16.46	0.21	−1.35	0.18	22/21	63.55	19.39	−0.76
THW < 0.9 s	−23.68	0.25	−1.66	0.10	22/21	47.82	14.59	−1.00

For the THW ranges THW < 1.35 s and THW < 0.9 s, we see negative mean differences with small effect sizes ($\geq$0.1, <0.3), implying that the duration of driving in these THW ranges was lower for participants driving with the stimulus activated. However, the mean differences in duration of driving in any of the THW ranges are not significant ($p < 0.05$) between the participants driving with stimulus in their first drive compared to participants driving without stimulus, suggesting no effect of the negative sound stimulus in these THW ranges. Hypothesis 1 states that the duration of driving in THW ranges <1.8 s is decreased for driving exposed to a negative acoustic stimulus controlled by the THW compared to driving without the stimulus. Based on the results, we cannot reject the null hypothesis (driving with stimulus leads to no decrease in the duration) based on the control group setup and, thus, reject the stated alternative hypothesis (H1).

The results of the one-tailed independent Mann–Whitney U-Test testing for the increase in mean THW driven in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) with stimulus are shown in Table 4.

Table 4. Results of one-tailed independent Mann–Whitney U-Test testing for the increase of mean time headway driven in the THW ranges while driving with stimulus compared to a control group driving without the stimulus: mean differences, effect size, Z-values, exact significances, sample size with/without stimulus, standard deviation, standard error, and the lower confidence interval. Significance levels: * = $p \leq 0.05$.

Mann–Whitney U-Test	**Comparison: Mean THWs in THW Range of First Drives of All Participants**							
THW Range	**Mean Difference**	**Effect Size**	**Z-Value**	***p***	**n per Stimulus**	**Standard Deviation**	**Standard Error**	**Conf. Interval (95%) Lower**
THW < 4 s	0.06	0.19	−1.22	0.22	22/21	0.32	0.10	0.69
THW < 1.8 s	0.10	0.30	−1.95	0.05 *	22/21	0.17	0.05	1.11
THW < 1.35 s	0.08	0.29	−1.91	0.06	22/21	0.12	0.04	1.15
THW < 0.9 s	−0.01	0.05	−0.36	0.72	22/21	0.09	0.03	0.45

From Table 4, it can be derived that there is only one significant ($p < 0.05$) positive mean difference with medium effect size (≥0.3, <0.5) for the mean THW in the THW range < 1.8 s between the participants driving with stimulus in their first drive compared to participants driving without stimulus. The significance of the mean difference in the THW range < 1.35 s with a close to medium effect size is slightly above the threshold of being significant, suggesting there could be a significant effect with a larger sample size. For the THW range < 0.9 s, the effect size is below the threshold for a relevant effect size. Hypothesis 2 states that the mean THW when driving in THW ranges < 1.8 s is increased when driving exposed to a negative acoustic stimulus controlled by the THW compared to driving without the stimulus. Based on the results, we can reject the null hypothesis (driving with stimulus leads to an increase in the mean THW) based on the control group setup and, thus, accept the stated alternative hypothesis (H2).

3.3. Descriptive Statistics Based on the Time Headway in the Within-Participants Setup

For the descriptive statistics of the within-participant comparison, the durations (in seconds) the participants were driving in the four different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) for the drives with vs. without the stimulus are compared first. Figure 11 shows the boxplots for the duration of driving in the THW over the whole of both drives with and without the stimulus of the participants.

Table 5 shows the means, the medians, and the standard deviation for the duration in seconds the participants were driving in the four different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) for both the drives with and without the stimulus.

For all of the THW ranges, the mean and median show a decrease for the drives with the stimulus. This indicates an effect of the stimulus on the duration people drove in THW in sight of a vehicle in front of them.

For the second comparison, we compare the mean THW in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) between the two drives of all participants with and without the stimulus. For each participant, only data from driving on the same lane in both drives is considered. Figure 12 shows the boxplots for the mean THWs over both drives of the participants. The number of samples for the THW ranges < 1.35 s and < 0.9 s is reduced due to participants not falling below 0.9 s THW. For the within-participant comparison, this impacts both drives due to the filtering process by the driven lane for both drives.

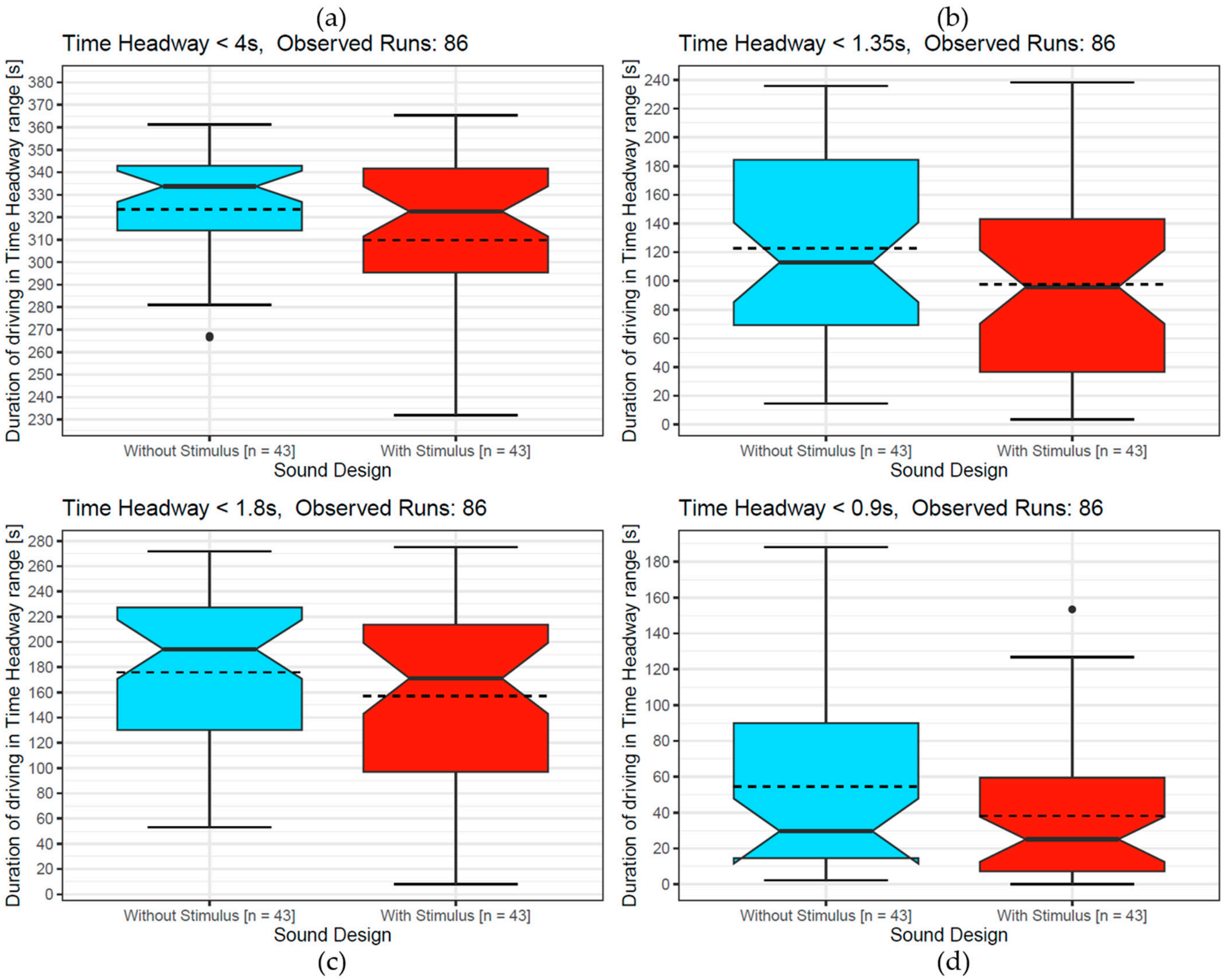


Figure 11. Box plots for the durations in seconds the participants were driving in the four different time headway ranges (THW < 4 s (**a**), THW < 1.8 s (**b**), THW < 1.35 s (**c**), and THW < 0.9 s (**d**)) for both drives of each participant with and without the stimulus. The lower and upper borders of the box represent the 1st and 3rd quartiles, respectively. The whiskers represent 0.25–1.5 IQR/0.75 + IQR (interquartile range), and outliers are drawn interdependently.

Table 5. Mean, median, and standard deviation of the durations in seconds the participants were driving in the four different time headway ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) with and without the stimulus.

Duration of Driving in THW Range (s)		Mean	Median	Standard Deviation	n
THW < 4 s	Without Stimulus	323.6	333.7	38.6	43
	With Stimulus	309.9	322.6	42.6	43
THW < 1.8 s	Without Stimulus	175.9	194.1	64.0	43
	With Stimulus	157.1	171.1	65.5	43
THW < 1.35 s	Without Stimulus	122.7	113.0	64.0	43
	With Stimulus	97.8	95.9	65.2	43
THW < 0.9 s	Without Stimulus	64.6	42.9	57.3	43
	With Stimulus	40.9	26.9	35.1	43

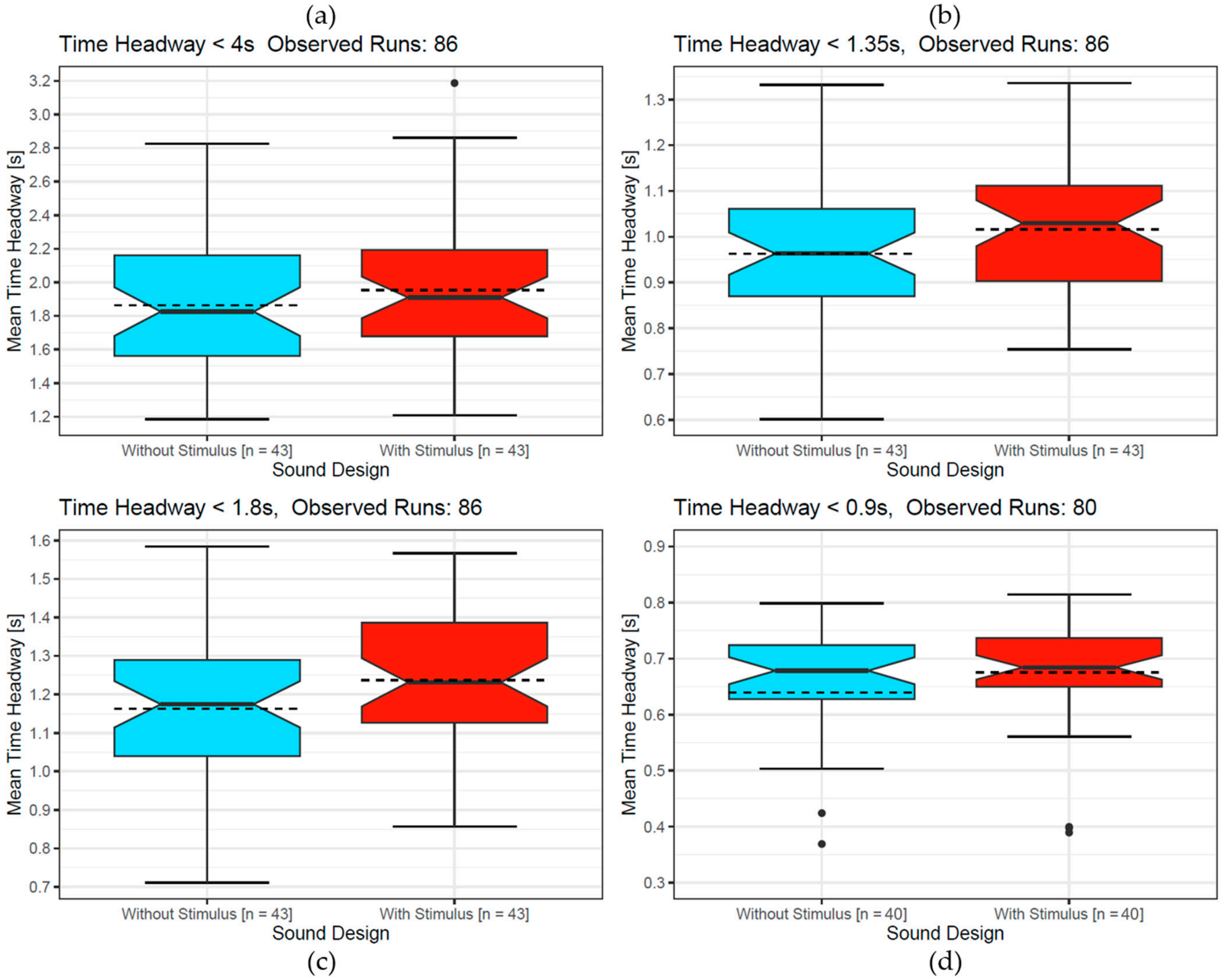


Figure 12. Box plots for the durations in seconds the participants were driving in the four different time headway ranges (THW < 4 s (**a**), THW < 1.8 s (**b**), THW < 1.35 s (**c**), and THW < 0.9 s (**d**)) for both drives with and without the stimulus while driving on the same lane. The lower and upper borders of the box represent the 1st and 3rd quartiles, respectively. The whiskers represent 0.25–1.5 IQR/0.75 + IQR (interquartile range), and outliers are drawn interdependently.

Table 6 shows the means, the medians, and the standard deviation over all the mean THWs in seconds the participants were driving in the four different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) for both drives with and without the stimulus.

For all of the THW ranges, the mean and median show an increase for the mean THWs for the drives with the stimulus. This indicates an effect of the stimulus on the chosen THW when following a vehicle in front of them.

Table 6. Mean, median, and standard deviation of the THW in seconds the participants were driving in the four different time headway ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) for both drives with and without the stimulus.

Mean THW in THW Range (s)		Mean	Median	Standard Deviation	n
THW < 4 s	Without Stimulus	1.86	1.83	0.39	43
	With Stimulus	1.95	1.91	0.41	43
THW < 1.8 s	Without Stimulus	1.16	1.17	0.19	43
	With Stimulus	1.24	1.23	0.19	43
THW < 1.35 s	Without Stimulus	0.96	0.96	0.14	43
	With Stimulus	1.02	1.03	0.13	43
THW < 0.9 s	Without Stimulus	0.63	0.68	0.14	40
	With Stimulus	0.66	0.67	0.10	40

3.4. Statistical Analysis of the Effect of the Stimulus on the Time Headway in the Within-Participant Setup

To test whether the emotionalizing sound design (stimulus) had an effect on the participants driving with and without the stimulus, a second statistical analysis was conducted. The method chosen is the one-tailed *Wilcoxon-Signed-Rank-Test* for repeated measures for pairwise comparison of the drives of one participant with and without the stimulus. For the first hypothesis, we test for a decrease in the duration driven in the THW ranges when the emotionalizing stimulus is active. For the second hypothesis, we test for an increase in the mean THW driven in the THW ranges when the emotionalizing stimulus is active. The one-tailed Wilcoxon-Signed-Rank-Test for repeated measures was implemented in R (Version 4.3.1) using the R-function *wilcox.test* of R's native stats package. The method was chosen because it allows for pairwise comparison of the increase or decrease in differences of at least ordinal dependent variables (durations of driving in THW range (s) or mean THWs (s)) based on a binary independent variable (with vs. without stimulus). The effect size was calculated from the Z-Value calculated by the *wilcox.test* function and the sample size. The results of the one-tailed Wilcoxon-Signed-Rank-Test for repeated measures testing for decrease in duration driven in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s) with stimulus are shown in Table 7.

Table 7. Results of one-tailed one-tailed Wilcoxon-Signed-Rank-Test for repeated measures testing for a decrease in duration of driving in lower time headway range while driving with stimulus compared to driving without the stimulus: mean differences, effect size, Z-values, exact significances, sample size with/without stimulus, standard deviation, standard error, and the upper confidence interval. Significance levels: * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$.

Wilcoxon-Signed-Rank-Test	Comparison: Duration Driving in THW Range of Both Drives within Participants							
THW Range	Mean Difference	Effect Size	Z-Value	p	n per Stimulus	Standard Deviation	Standard Error	Conf. Interval (95%) Upper
THW < 4 s	−13.70	0.25	−2.32	0.02 *	43/43	40.63	8.76	−0.69
THW < 1.8 s	−18.77	0.26	−2.42	0.02 *	43/43	64.76	13.97	−0.65
THW < 1.35 s	−24.90	0.34	−3.19	0.001 **	43/43	64.59	13.93	−0.74
THW < 0.9 s	−16.52	0.45	−4.17	0.0001 ***	43/43	47.05	10.15	−0.71

From Table 7, it can be seen that all the mean differences within participants are significant ($p < 0.05$) for the duration of driving in THW ranges, with at least a small effect size between a participant driving with stimulus compared to driving without stimulus. The mean duration of driving in these THW ranges was lower for all THW ranges when driving with the stimulus activated, suggesting a reducing effect of the negative sound stimulus on the duration of driving in the lower THW ranges. For the THW ranges THW < 1.35 s and THW < 0.9 s, we further see highly significant negative mean differences with medium effect sizes, suggesting an even stronger effect when the sound stimulus is targeted to sound more threatening. Hypothesis 1 states that the duration of driving in THW ranges <1.8 s is decreased when driving exposed to a negative acoustic stimulus controlled by the THW compared to driving without the stimulus. Based on the results, we can reject the null hypothesis (driving with a stimulus leads to no decrease in the duration) and thus accept the stated alternative hypothesis (H1) in the within-participants comparison setup.

The results of the one-tailed Wilcoxon-Signed-Rank-Test for repeated measures testing for the increase of mean THW driven in the THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s and THW < 0.9 s) with stimulus are shown in Table 8.

Table 8. Results of one-tailed one-tailed Wilcoxon-Signed-Rank-Test for repeated measures testing for the increase in mean time headway driven in the THW range while driving with stimulus compared to without the stimulus: mean differences, effect size, Z-values, exact significances, sample size with/without stimulus, standard deviation, standard error, and the lower confidence interval. Significance levels: * = $p \leq 0.05$, ** = $p \leq 0.01$.

Wilcoxon-Signed-Rank-Test	Comparison: Mean THWs in THW Range of Both Drives within Participants							
THW Range	**Mean Difference**	**Effect Size**	**Z-Value**	***p***	**n per Stimulus**	**Standard Deviation**	**Standard Error**	**Conf. Interval (95%) Lower**
THW < 4 s	0.09	0.26	−2.41	0.02 *	43/43	0.40	0.09	0.58
THW < 1.8 s	0.07	0.35	−3.24	0.001 **	43/43	0.19	0.04	0.75
THW < 1.35 s	0.05	0.35	−3.22	0.001 **	43/43	0.14	0.03	0.74
THW < 0.9 s	0.04	0.19	−1.70	0.09	40/40	0.12	0.03	0.67

From Table 8, it can be derived that there were significant and positive mean differences with at least a small effect size for the mean THW in the THW ranges THW < 4 s, < 1.8 s, and < 1.35 s between a participant driving with stimulus compared to driving without stimulus. The mean differences in the THW range < 1.8 s and < 1.35 s further have a medium effect size and are highly significant. Also, the mean differences in all THW ranges are positive due to the higher mean THW while driving with the negative sound stimulus compared to driving without. However, the difference in mean THW in the THW range < 0.9 s was not significant, although, for the duration, we saw a highly significant effect in this THW range. Hypothesis 2 states that the mean THW when driving in THW ranges < 1.8 s is increased for drivers exposed to a negative acoustic stimulus controlled by the THW compared to drivers without the stimulus. Based on the results, we reject the null hypothesis (driving with stimulus leads to no increase in the duration). Therefore, we accept the stated alternative hypothesis (H2) in the within participants comparison setup.

3.5. *Affective Evaluation of the Stimulus*

To investigate the emotional effect of the stimulus, the 43 participants were asked about how they felt when exposed to the stimulus in an open question. Figure 13 illustrates the frequencies of stated emotional descriptors chosen by participants when answering the question, " How did you feel when the sound changed?".

Feeling unsafe or threatened (the targeted emotions) were stated 15 times in the answers by 12 participants. Feeling annoyed or disturbed was reported 15 times by 14 participants. The most frequently chosen descriptor was uncomfortable, with 19 mentions. Being stressed was stated nine times.

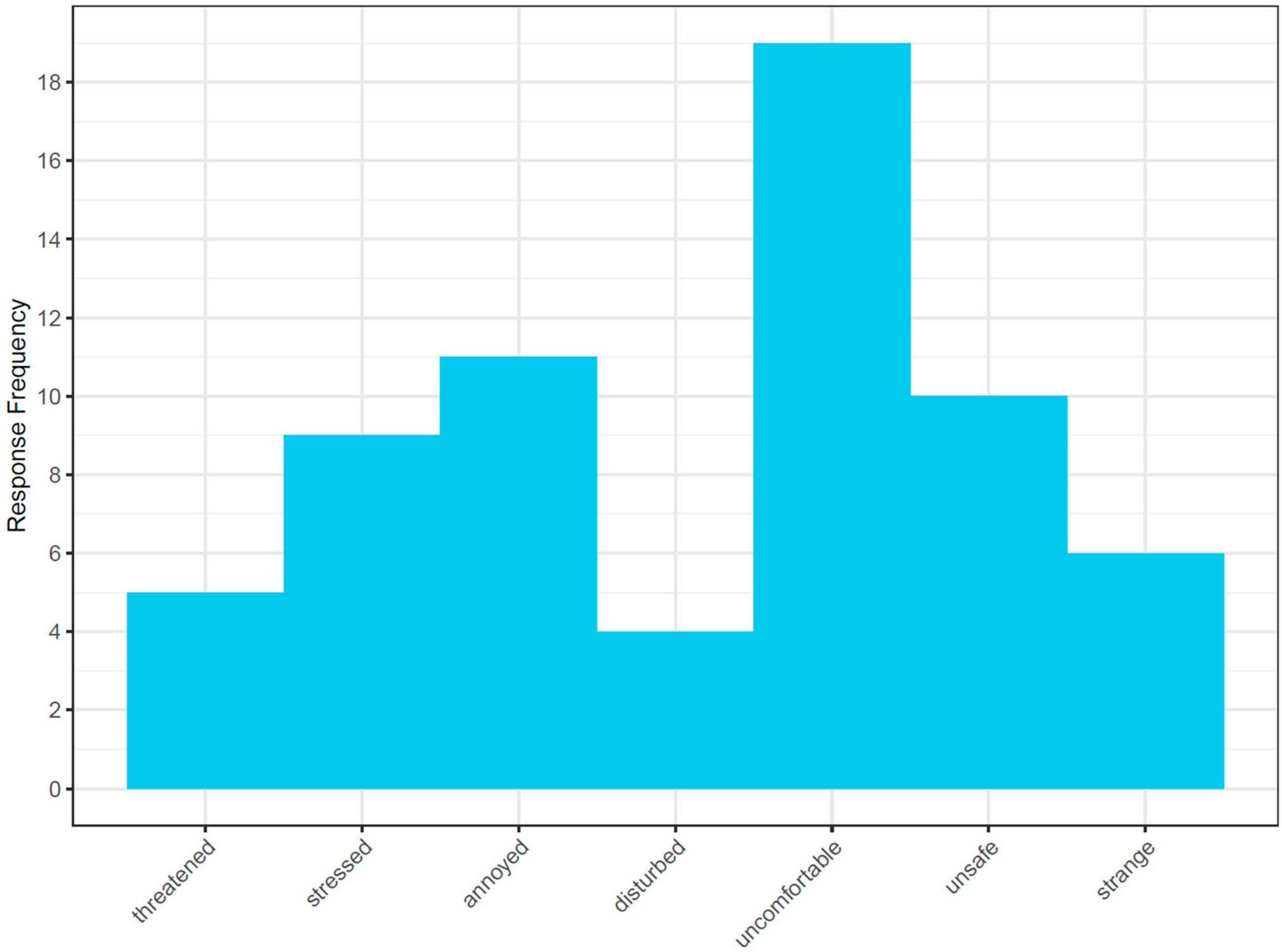


Figure 13. Frequency of responses of stated emotional descriptors chosen by participants when answering the question, " How did you feel when the sound changed?".

To quantify how much of the participants connected the change in sound to the THW, an additional question was asked. A total of 19 of the 43 participants connected the change in sound explicitly to the THW or to approaching the vehicle ahead when asked, "In what situation did you notice this change in noise?".

4. Discussion

In this paper, we tested whether the emotionalizing sound design we created had an effect on the duration of driving in lower THW ranges and the mean THW in lower THW ranges. We investigated potential effects in four different THW ranges (THW < 4 s, THW < 1.8 s, THW < 1.35 s, and THW < 0.9 s). We further proposed two hypotheses supported by the state of research for testing whether the emotionalizing sound design might have a positive effect on traffic safety in regards to safety distance suggested by the German Federal Motor Transport Authority [5]: Hypothesis 1: The duration of driving in THW ranges < 1.8 s is decreased when driving exposed to a negative emotionalizing acoustic stimulus controlled by the THW compared to driving without the stimulus. Hypothesis 2: The driven mean THW is increased in time headway ranges < 1.8 s when driving exposed to a negative emotionalizing acoustic stimulus controlled by the THW compared to driving without the negative stimulus. To test the effect of the emotionalizing sound design and the hypotheses, we compared driving with the stimulus, an emotionalizing sound design changing from a positive sound to a negative, threatening sound based on the current safety distance, vs. driving just with the positive sound (without stimulus). The participants conducted two drives in total. Whether they first drove with the emotionalizing sound design or just the positive sound design was randomized. A comparison was first performed in a control group setup for the analysis where only the first drive in the simulator of the participants randomly, with or without the emotionalizing sound, was considered. In the second analysis setup, we compared the duration of driving in low THW ranges and mean THW within participants by comparing both drives of each participant with and without the stimulus.

For the control group setup, when testing for the decrease in duration of driving in lower THW ranges with the stimulus, there were substantial decreases for the durations driving in the lower THW ranges (THW < 1.35 s and THW < 0.9 s). However, these differences were not statistically significant. Based on these results, the first Hypothesis was rejected for the control group setup. For the mean driven THW in low THW ranges, we only found a just significant medium-sized effect in the mean THW differences driving in the THW range < 1.8 s for the participants driving with the emotionalizing sound design vs. participants driving without. Based on this result, the second Hypothesis was accepted for the control group setup. However, it is necessary to mention that the results for the other THW ranges showed no significant increase in the mean THW while driving with the emotionalizing sound design.

One explanation for not reaching significance in the control group setup for most of the considered THW ranges could be the ineffectiveness of the stimulus. An alternative explanation may be the small sample size in the control group setup, consisting of 21 participants driving with the stimulus and 20 driving without. This sample size might have failed to ensure an equitable distribution of driving styles between the groups despite their random composition, leading to a masking of the effect of the emotionalizing stimulus.

In the within-participant comparisons, significant reductions in driving duration were observed across all THW ranges when exposed to the stimulus. This substantial change supports acceptance of the first hypothesis in this specific context. The within-participant comparisons for mean THW revealed significant increases in all but the smallest THW range (THW < 0.9 s). The results show that the driving behaviour of participants was influenced and systematically altered except for the mean THW in the possibly unsafe and, in Germany, inadmissible THW range < 0.9 s. Based on these results, the second hypothesis was accepted in the within-participant design.

The authors see two major potential reasons why there were no significant differences in the THW range < 0.9 s. The first is that at the THW range < 0.9, the emotionalizing sound design is at the maximum negative setting. In this setting, the sound is exactly the same sound as the newly developed threatening sound tested in a previous study [31]. In the last study, this sound showed significant effects on the estimation of a shown safety distance. However, there were no significant effects on the evaluation of the shown safety distance as appropriate or the desired increase of the depicted safety distance. Despite the previous results, we selected this particular sound for our study for two main reasons: Firstly, it represented a logical progression in efforts to enhance the sound's threatening effect, informed by previously identified correlations between psychoacoustic parameters and the perception of sounds as threatening [30]. Further, we wanted to investigate if a video-based experimental setup was not close enough to reality for the sound to be an effective stimulus. In this simulator study, the duration of driving in this <0.9 s THW range was drastically lower (58%), and the difference was significant when stimulated with this sound, whereas the mean THW was increased by 5%, albeit not significantly. This potentially reflects the results of the previous study that the sound was evaluated as threatening and uncomfortable, and thus, people potentially spent less time in THW ranges with this sound, but it did not motivate them to increase the THW when stimulated by it. The explanation could be, again, that because of its high level of impulsiveness and fluctuation strength at around 2 Hz (which sounds potentially similar to aggressive techno or comparable electronic music), there could have been an effect similar to the influence of music tempo on driving in a simulation [15]: a higher tempo in music was observed to increase speeds and higher occurrence of traffic violations. This underlines the strong indication that frightening or threatening emotionalizing sound design could effectively influence the choice of THW in the following car scenarios. Based on our findings, the affective sounds should be achieved by increasing the amount of dissonance of the sounds and the addition of modulated metallic hissing sounds. However, high levels of impulsiveness and fluctuation strength that possibly resemble higher-tempo music should be avoided. Furthermore, the observed larger effect size and increased statistical significance in the duration of driving with a THW of less than 0.9 s when the stimulus was present could be attributed to participants' reluctance to drive in an annoying or disturbing soundscape. This suggests that the reduction in driving duration may not necessarily reflect an active effort to increase the THW and reduce the perceived threat but rather a desire to avoid the unpleasant soundscape. Comparative data from the previous video-based study [31] with the same sounds as used in this simulator study revealed that 62% of participants felt threatened or afraid while listening to the sound hearable at 1.35 s THW, and 68% when listening to the sound below 0.9 s THW. In contrast, in this simulator study, when prompted with an open-ended question regarding their reactions to the sound changes, 'threatened' or 'unsafe' were descriptors used by 12 of the 43 participants (28%) to articulate their feelings. In contrast, 14 participants (33%) reported feelings of annoyance or disturbance. This also could indicate that subjects evaluate the sounds differently when sitting in an actual car compared to just imagining sitting in the car while listening to sound stimuli.

5. Conclusions

In conclusion, our investigation into the impact of an emotionalizing sound design on driving behaviour has produced indicative results. The study aimed to determine the influence of an acoustic stimulus, which varied from positive to negative/threatening sounding based on the vehicle's time headway (THW), on driving durations within specific THW ranges, and on the mean THW itself. Our findings revealed a dichotomy between control group setups and within-participant comparisons. The control group did not show significant reductions in the duration of driving at lower THW ranges overall; however, notable decreases were observed at extremely low THWs. This outcome led to the rejection of our first hypothesis for the control group, which anticipated reduced driving times at THWs below 1.8 s with the stimulus. The mean THW showed a modest but significant increase when the emotionalizing sound was activated for the THW range below 1.8 s. This supports the stimulus' efficacy in encouraging safer driving habits, leading to the acceptance of our second hypothesis. More profound insights were gained from within-participant comparisons, which demonstrated both a significant decrease in the duration of driving at lower THWs and an increase in the mean THW when the negative stimulus was active. These results affirm the stimulus' potential to influence driver behaviour toward maintaining safer distances, aligning with the expected outcomes of the first and second hypotheses. Interestingly, significant improvements were also observed in the highest THW range < 4 s. This may indicate that the influence of the stimulus on the chosen safety distance persists even when participants are no longer actively experiencing the negative or threatening sound due to currently driving in THW > 1.8 s. This finding suggests a residual impact of the stimulus on driver behaviour beyond immediate stimulus exposure. Participant feedback indicated varied emotional responses to the sound changes, with feelings ranging from threat and discomfort to annoyance, highlighting the subjective nature of auditory influence on driving behaviour. The lack of significant effects in the potentially unsafe THW range below 0.9 s, where the stimulus was at its most negative, suggests a ceiling effect of negative emotionalization or possible desensitization to the sound. This finding aligns with previous research indicating that certain sound characteristics, akin to those in aggressive music, might not effectively promote safer driving despite increasing alertness or stress levels. Future research should explore alternative emotionalizing sounds that might yield more consistent behavioural adjustments across different THW ranges. This also includes the investigation of emotionalizing sound design yields stronger effects when used as positive reinforcement for rewarding adequate driving behaviour. Further, the research could expand the practical applications of auditory stimuli in other driving contexts, such as speeding or rewarding economical driving.

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