Relationship between the psychoacoustic parameter sharpness and the physiological parameter skin conductance for the assessment of extra-aural noise effects

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Introduction

The ubiquitous problem of noise exposure occurs in many different situations where people might not even notice directly that they are exposed to harmful environmental noise. In the case of traffic noise alone, the WHO estimates that more than 100 million people in Europe are affected by this type of noise exposure, resulting in the loss of about 1.6 million healthy life years in Western Europe [11].

When considering the negative consequences of noise on humans, two different categories of health effects can be distinguished. On the one hand, the aural noise effect describes the direct damage to the hearing system. On the other hand, the term extra-aural noise effect describes damage which could effect the entire organism [1]. This concerns health problems not directly related to hearing, such as physiological and psychological stress caused by noise as well as losses of performance and concentration. For an appropriate noise assessment it is important to include both categories of noise effects in the assessment. Stress reactions are mechanisms intended to help an organism to cope with potentially dangerous situations. However, if stress situations occur too frequently, it can lead to long-term damages, for example in the form of cardiovascular diseases [7].

When the body is confronted with a stressor, such as noise, the sympathetic nervous system (SNS) becomes active. The involved SNS is considered to be the nervous system that activates the body. Together with the parasympathetic nervous system (PSNS), it forms the autonomic nervous system of the human body [3]. Activation of the SNS leads to numerous physiological changes in the body. In addition to an increased heart rate or breathing rate, which should prepare us for a fight or a flight in dangerous or stressful situations (Fight-or-Flight-Reaction), sweat production in the palms and soles of the feet is also increased, referred as Electrodermal Activity (EDA) [2].

Suitable sensors allow researchers to detect these physiological changes associated with a stress response to draw conclusions about the level of activation of the SNS. One of the most commonly used parameters is the measurement of Skin Conductance (SC) which is used to capture the EDA. For this purpose, two electrodes are attached to the hand with a constant voltage applied. The Skin Conductance is then proportional to the measured current. Increased sweat production in the hand leads to an increase in Skin Conductance. Measuring Skin Conductance has the advantage that the skin is the only human organ that is controlled exclusively by the SNS and is not influenced by the PSNS [4].

In contrast to previous research this study does not investigate the stress response in relation to a specific realistic acoustic stressor, but in relation to a property of an acoustic stressor, the sharpness of a sound event. In previous research the sharpness has been related to listeners sensations using self-reported metrics and is often associated with a higher annoyance [8]. Therefore, a higher stress response was expected for sounds of higher sharpness. The use of physiological parameters, as compared to the sole use of the self-reported information on psychoacoustic parameters, offers a further measurable dimension to show the negative effects of stress and thus allows a better classification of sounds with respect to the extra-aural noise effects on humans.

Methods

Participants

A total of 29 participants (age: 22-30 years; M = 25.5 years, SD = 1.5 years, 15 female) took part in the experiment. Before the experiment started, informed consent was obtained from each participant for the whole procedure of the experiment, especially for the application of non-invasive electrodes to the subjects' bodies.

Stimuli

In order to investigate the influence of sharpness individually, synthetic signals were used, which are well suited to keep other parameters constant, such as loudness. In total, three different levels of sharpness were used within the stimuli. Noise with the bandwidth of the critical bands number 2 (CB 2: 0.32 acum), 12 (CB 12: 1.34 acum) and 21 (CB 21: 5.58 acum) was selected. The sharpness was calculated according to DIN45692 [5]. All stimuli had a uniform loudness at 18 sone.

Cognitive Test

The participants had to perform a cognitive test, while they were exposed to the acoustic stimuli. Performing cognitive work should more realistically represent a typical work environment than inactivity. Therefore, we introduced a controlled activity which was the same for all participants. Additionally, a test provides the opportunity to examine the losses in cognitive performance as another extra-aural effect.

A test that fulfils the requirements of a simultaneous measurement of skin conductance is the Konzentrations-Leistungs-Test (KLT) in the revised version [6]. The computerization of the KLT is based on the computerization according to Schlittmeier et al. [9]. During sessions of two minutes the participant worked on several trials of the test in succession. Each trial consisted of two arithmetic problems, whose results had to be combined to a final result at the end. For the arithmetic problems, three single-digit numbers were added together. The numbers were visible for 700 ms followed by a pause of 300 ms. When the second problem was finished, the final result had to be entered using a numeric keypad, where the numbers from zero to nine were displayed in random order. As a performance indicator the error rate was used taking into account the amount of totally completed trials within the two minutes and the number of incorrectly solved trials.

Experimental Design

Before the experiment, the participants were asked to get into a comfortable sitting position and place the arm of the non-dominant hand on the table. Afterwards, the test supervisor attached the sensors. The hand to which the sensors were attached should be held with the palm upwards so that they could not be pressed on the table during phases of tension, which would improve contact with the electrodes.

The experiment consisted of twelve sessions of the KLT of two minutes length, while the different acoustic stimuli were presented separately. This resulted in four conditions, performing of the KLT with one of the three stimuli and performing of the KLT without presentation of an acoustic stimulus. The conditions were repeated three times. Between the individual conditions, rest periods of 30 seconds were placed. During these rest periods, the participant was supposed to remain seated quietly and did not hear any acoustic stimuli. Since the typical Time of 50 % recovery is between two and ten seconds [2], the duration of 30 seconds was chosen to ensure a full recovery of the stress response. The order of the conditions was counterbalanced using a Latin Square between all participants. Two identical conditions never followed each other directly. The experiment started with a training session of the KLT and a four-minute baseline measurement. After the baseline measurement, a session of the KLT was performed without acoustic stimulus. This condition was not part of the twelve sessions and was not included in the evaluation because the participant was faced with an unexpected situation after a long resting period.

Experimental Environment

The experiment took place in the listening studio of HEAD acoustics with a constant room temperature. The acoustic stimuli were presented using calibrated and equalized hardware from HEAD acoustics via Sennheiser HD 650 headphones. Like the KLT, the complete experiment was created in HEAD acoustics' SQala software utilizing the SQala Extension API. The measurement of the physiological data of skin conductance and respiration were recorded using the g.GSRsensor and the Respiration Effort Sensor of the g.tec medical engineering GmbH as shown in Figure 1. For the measurement the electrodes were applied to the index finger and the middle finger of the non-dominant hand of the participant. The sensors were connected to the g.USBamp Research Amplifier.

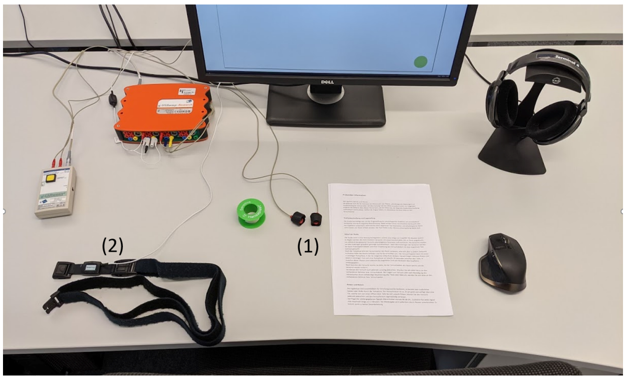

Figure 1: Experimental environment in the listening studio of HEAD acoustics. The sensors for measuring skin conductance (1) were attached to the fingers of the non-dominant hand. The sensor for measuring respiration (2) was placed just below the chest.

Data Evaluation

The data was first filtered by the data recorder software with a low pass at 30 Hz as recommended by the sensor manufacturer. Fast motion artefacts were thus eliminated. In addition the notch filter at 50 Hz was added to avoid artefacts caused by the power line noise in the signal. The measurement data were then checked for non-responders. Non-responders are participants characterized by hypo-responsiveness to stimuli [2]. Among the 29 participants of this study there was one non-responder, whose data were not included in the evaluation.

Further artefact corrections were applied by examining the respiration in parallel for irregularities by visual inspection. Increases in skin conductance, that occurred shortly after a deep breath and fell into one of the resting periods, were considered as a non-emotional response according to Boucsein [2] and removed. For the retrospective removal of motion artefacts, an algorithm for wavelet based artefact correction was implemented and applied to the skin conductance data [10].

For a final quantification of a stress response the Skin Conductance data was separated into a tonic and a phasic level. Both components provide features that contribute to a more precise analysis. The tonic level (Skin Conductance Level (SCL)) describes the slowly changing part of the signal and therefore reflects the base arousal level of a person. The phasic part of the signal, however, contains the rapidly changing component of skin conductance. From this, fast reactions of sweat production can be derived, which are also called Skin Conductance Response (SCR) or Non Specific Skin Conductance Response (NS-SCR) if they are not related to a single short stimulus. For an inter-individual comparison, the signals were finally normalized by a z-Score.

For experiments where the level of activation of the SNS is to be measured over a longer period of time ($> 20\,\mathrm{s}$), so-called tonic features are more suitable for analysis [2]. On one hand, the increase of SCL from the resting period to the following test phase of the KLT was calculated. On the other hand, the phasic level can also be used here to consider the number of NS-SCRs in a certain period of time as a feature. The frequency of NS-SCRs per minute is usually given, which increases for a higher level of activation of the SNS. An example for both features is shown in Figure 2.

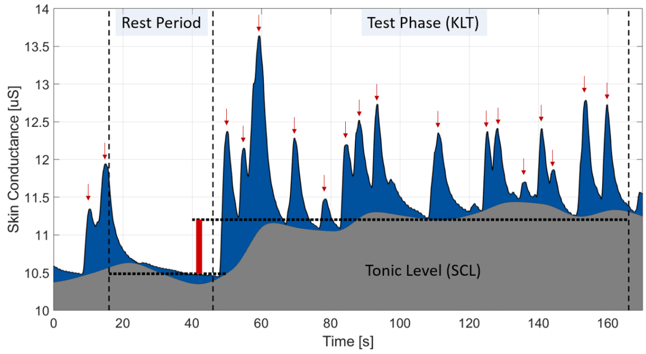

Figure 2: Scoring of a stress response by the increase in SCL between the resting period and test phase and the frequency of NS-SCRs. The mean SCL values of the individual phases are marked by the horizontal dotted lines. The difference between the two mean values is indicated by the red bar. The NS-SCRs are marked by red arrows.

Results

Physiological Data

For the physiological stress measurement, the increase in the z-Score corrected SCL was first evaluated as a score for the stress response. This resulted in a mean increase of SCL by 0.1 (SD = 0.49) for processing the KLT in silence. Under the acoustic stimulus CB 2, the mean increase in SCL went up to 0.18 (SD = 0.53). When the other stimuli CB 12 and CB 21 were presented, the mean increase went up further to 0.27 (SD = 0.64) and 0.32 (SD = 0.48). After verification using the Shapiro Wilk Test ($p > .05$ in all cases), a normal distribution was found for all conditions. Thus, the one-way repeated measures ANOVA could be performed, that showed significant differences of the mean values (F(3,332) = 2.85, p = .038, $\eta_g^2 = 0.03$). In the subsequent post-hoc test the pairwise t-test with Bonferroni correction showed a statistically significant difference in the stress response between the conditions Silence and CB 21 (p = .01) as indicated in Figure 3. Differences between the other comparisons of the conditions were not significant.

The frequency of the NS-SCRs was evaluated as the second score for the physiological stress response. This resulted in an average standardized frequency of -0.3 (SD = 0.85) for the condition Silence. Higher mean values were present for the conditions with acoustic stimuli. Here mean values of -0.085 (SD = 0.952) for CB 2, 0.096 (SD = 0.785) for CB 12 and 0.288 (SD = 0.927) for CB 21 were measured. A normal distribution was not present for any of the conditions according to the Shapiro Wilk test ($p < .05$ in all cases). The Friedman test was therefore used for statistical analysis, that indicated significant differences ($\chi^2(3) = 18.49$, $p < .001$). In the course of the Wilcoxon Test with Bonferroni Correction as a subsequent post-hoc test, there was a significant increase in the stress response between Silence and CB 12 (p = .015) and between Silence and CB 21 ($p < .001$), as it is visualized in Figure 4. The difference between Silence and CB 2 was not significant ($p > .05$). Analysing the conditions with acoustic stimuli, there was a significant higher stress response in the condition CB 21 compared to the condition CB 2 (p = .010).

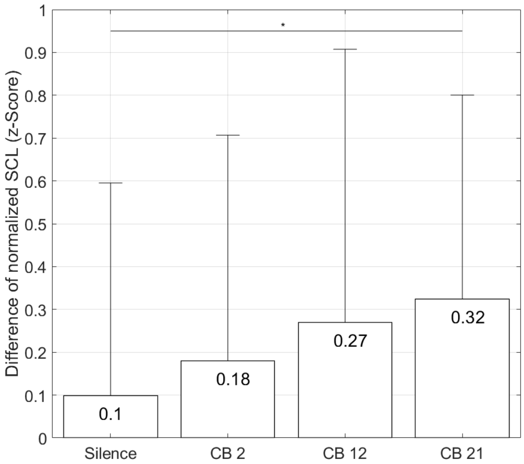

Figure 3: Results of the increase of normalized SCL for the individual sessions of the KLT in silence and with the acoustic stimuli of noise in critical frequency band 2 (CB 2), critical band 12 (CB 12) and critical band 21 (CB 21).

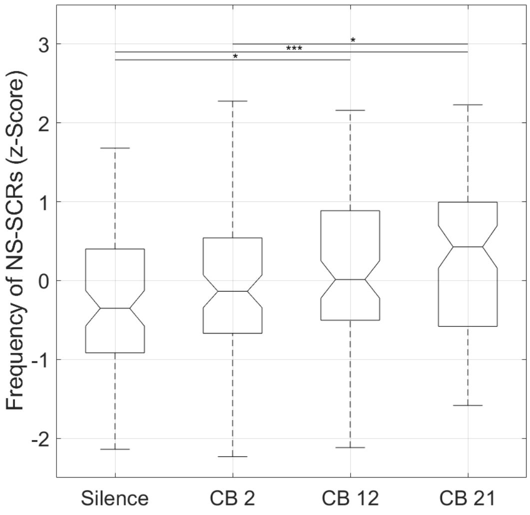

Figure 4: Boxplot of the frequency of NS-SCRs per minute for the individual conditions of the KLT.

Cognitive Test Performance

According to Schlittmeier et al. [9] the error rate was used as the score of the KLT to investigate the reduction in cognitive performance. For the condition Silence an average error rate of 20.0% (SD = 17.6), for the condition CB 2 an error rate of 19.6% (SD = 17.9) and for the condition CB 12 an error rate of 17.1% (SD = 16.0) was determined. For the CB 21 condition, the mean error rate was at only 11.9% (SD = 13.6). For all conditions, no normal distribution was present after verification by the Shapiro Wilk test ($p < .05$ in all cases). The Friedman Test showed statistically significant differences between the conditions ($\chi^2(3) = 9.42$, p = .024). The post-hoc Wilcoxon Test with Bonferroni correction showed that these were the differences in the significantly lower error rate when performing the KLT with the CB 21 stimulus as compared to the other conditions, Silence (p = .002) and CB 2 (p = .008). This is visualized in Figure 5. No significant difference was found between the other conditions.

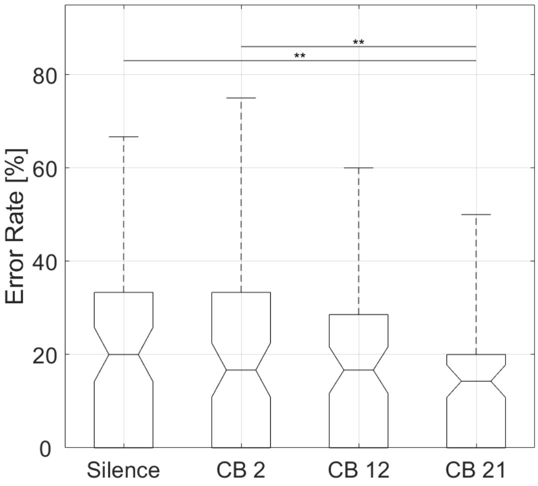

Figure 5: Boxplot of the error rate in the KLT for the individual conditions.

Conclusion

The evaluation of the collected data could confirm a suspected relationship between the sharpness of a sound and the physiological stress response. The evaluated measurement data could indeed detect an increased stress responses in the presence of a noise with high sharpness. This coincides with the higher annoyance of noises with high sharpness found in previous research [8]. No significant difference in the stress response could be found between working the KLT in silence and with the noise of lowest sharpness. This also coincides with the low annoyance for sounds of low sharpness.The difference in the stress response between the noise of low and high sharpness, as demonstrated by the frequency of NS-SCRs, indicates that the activation of the sympathetic nervous system is significantly higher when the noise is of higher sharpness. Noises of higher sharpness, therefore, might have a greater potential to cause the health effects mentioned above. The results of our study suggest that sharpness should be included in noise control assessments to consider increased activation of the sympathetic nervous system.

Regarding the cognitive test, the significant increase in performance in sessions of the KLT with the sound of high sharpness should be highlighted. According to the capacity-resource approach, stress exhausts attention resources, resulting in a reduced use of task-irrelevant processing in the brain. The human body turns into the fight-or-flight reaction and needs brain resources to assess the stressor and to control it. Related to the experiment conducted in this study, an increased stress response due to the higher sharpness of the noise possibly caused higher focus when dealing with the arithmetic problems. This is consistent with the feedback of the participants, where the majority reported that thoughts were more often digressed in silence and thus intermediate results were forgotten. In contrast, the sharpness of the noise made them feel more attentive and concentrated on the task.

In future studies, attention should be paid to the cognitive test. Since different cognitive processes are differently disturbable by noise, cognitive processes representing typical noise-sensitive activities in the workplace should be chosen. The KLT was suitable for a first investigation of physiological responses, but if the performance increasing effect of sharp sounds can be maintained for longer test duration or more difficult/different cognitive tasks remains to be examined. Furthermore, other physiological parameters such as heart rate variability or brain activity in the form of an EEG could be added to obtain even more precise information about the state of the body.

Additionally, future studies could examine the effect of other psychoacoustic paramters and utilize sounds which closer represent typical work related noises.

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