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Contribution of single sounds to sound quality assessments of multi-source environments

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ABSTRACT

In everyday life people are surrounded by several sound sources which complement each other in complex acoustical environments. Different models to predict annoyance reactions to combined noise sources, predominantly based on loudness summation, have recently been proposed. However, it is still not understood how single sounds contribute to the evaluation of pleasantness of a multi-source environment, as the perceived sound quality is subject to numerous superposition and interaction effects of sounds with diverse acoustical characteristics. Therefore, the fundamental relationship between assessments of single and combined sound sources was investigated in the course of a listening experiment. Various sounds commonly occurring in suburban areas, including traffic noise, sounds from technical devices and natural sources, were evaluated in laboratory separately and combined in pairs with regard to their pleasantness. The results show that the combination ratings correspond to the sum of the single assessments and their interaction ($R^2 = .95$). Moreover, less pleasant sounds have greater influence than pleasant sounds, which can be attributed to masking effects and the negativity bias. A regression model is proposed that provides a highly accurate prediction for simple sound combinations in laboratory context. Consequently, validation for acoustical environments of higher complexity is needed in future.

Keywords: Sound Quality, Evaluation, Multi-source environments I-INCE Classification of Subjects Number(s): 01.7, 63, 69

1. INTRODUCTION

In everyday life people are surrounded by several sound sources which complement each other in complex acoustical environments. Multiple sounds with diverse acoustical characteristics and spatial distribution interfere with each other and form an overall noise scenario that is subject to various interaction effects, for example spectral and temporal masking. The perceived sound quality of a multi-source environment is affected not only by acoustical parameters but also by information from different sensory modalities, e.g. visual stimuli, and cognitive factors like attention and habituation. Moreover, context variables like personal attitude towards an environmental noise have an influence on its subjective evaluation (1). As a consequence, sound quality assessments in complex environments require interdisciplinary methodology to obtain ecologically valid results.

Although powerful metrics exist to describe human evaluation of singular auditory events, it is still not understood how different types of sounds contribute to the subjective evaluation of sound quality in a multi-source environment. To predict traffic noise annoyance from multiple sources, several competing models have been developed in the past. Prevalently, these models are based on energetic summation of single noise sources or loudness summation. The dominant-source-model (2) assumes that the overall annoyance in an acoustical environment corresponds to the annoyance level of the most disturbing noise source being present. Although this model corresponds well with empirical data regarding noise scenarios with one predominant source, its predictive power decreases significantly when multiple sources with similar loudness or annoyance occur (3). Therefore, other models include data from dose-response-curves to determine perception-based correction terms for the calculation of overall annoyance (4). Due to the fact that road, railway and airplane noise with equal sound level have different effect on people regarding annoyance, the annoyance-equivalent-

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model (5) uses a reference source to determine the annoyance of combined sources. The noise from individual sources is transformed into the equally annoying sound levels of road traffic noise. Then the overall annoyance is determined based on the sum of these levels. However, no uniform threshold for subjective noise annoyance can be detected in dose-response-curves. Miedema and Oudshoorn found great inter-individual differences in annoyance reactions even for high noise levels (6). In addition, recent field and laboratory studies reveal great differences in results concerning the cumulative effect of different traffic noise sources (7). This complicates a model-based estimation of annoyance in multi-source environments.

Moreover, annoyance is not the only evaluation criterion concerning the sound quality of an acoustical environment. The previously discussed models are focused on the disturbing effect of multiple combined sound sources. Nevertheless, sound should also be considered as a positive resource. Natural sounds for example can significantly enhance the sound quality in urban environments, although they represent additional sound sources and possibly increase the overall sound pressure level. De Coensel et al. (8) showed, for instance, that sounds from birds and water fountains contribute to an improved perception of acoustical scenarios with a high amount of road traffic noise. This example illustrates that the evaluation of sound quality is particularly subject to affective and cognitive factors which are not represented by psychoacoustical metrics and sound pressure levels. This includes that human perception of an acoustical environment is associated with selective attention. The saliency of a sound, which according to Betsch et al. (9) is specified as dissimilarity and conspicuousness of a stimulus in relation to its context, thereby moderates the focus of auditory attention. Consequently, a natural sound can distract the listener from other environmental sounds and hence alter the overall impression of the acoustical environment.

The evaluation of an unpleasant sound can originate not only from its acoustical saliency, but also from the fact that human evaluation strategies in general are presumably liable to a negativity bias. This effect, described by Rozin and Royzman (10), indicates that, based on predispositions and experience, negative events receive greater weight compared with equivalent positive events. One of four aspects of negativity bias is negativity dominance: the combination of negative and positive entities results in an evaluation which is more negative than the evaluations of the singular entities in sum. In psychological research, this effect has been observed in several different domains. Concerning the evaluation of combined sounds, negativity dominance may be expected similarly. Beyond that, a potential influence of positivity bias, which was discussed by Matlin and Stang, inter alia, in conjunction with memory processes (11), has to be considered with regard to current evaluations of multi-source scenarios as well.

To describe sound quality evaluation of complex acoustical environments, the fundamental interaction mechanisms between singular sounds and their impact on the overall evaluation have to be investigated in detail. According to Axelsson et al., the three basic dimensions *Pleasantness*, *Eventfulness* and *Familiarity* describe human perception of a complex acoustical environment (12). A *Pleasantness* judgment already integrates perception-based processing of acoustical properties as well as cognitive processing on a higher level. Against this background the question arises, if we can predict the overall *Pleasantness* of combined sounds based on their singular *Pleasantness* ratings. Therefore, a model-based approach with singular and combined quasi-stationary sounds was investigated in the course of a listening experiment at Duesseldorf University of Applied Sciences.

2. LISTENING STUDY

The underlying hypothesis was that the overall evaluation of *Pleasantness* in a multi-source environment can be explained as the weighted sum of the singular *Pleasantness* ratings and an interaction variable. The interaction is supposed to be a combination of masking effects between both sounds and a negativity bias which leads to a higher weighting of unpleasant sounds. In order to focus on acoustical effects in the first step and to control influence factors with the highest possible degree the experiment was conducted under laboratory conditions and exclusively acoustical stimuli were presented. 25 persons (7 female, 18 male) participated in the experiment (mean age: 32.4 years, SD: 11.2 years). The participants were employees and students of Duesseldorf University of Applied Sciences.

2.1 Stimuli

Stereo recordings of quasi-stationary sounds which usually occur in residential areas were taken from a sound database. In the course of a pretest, 8 different sounds were selected which had to represent four different degrees of *Pleasantness* in this laboratory context and span the full range of a subjective rating scale. Thus, for each degree of *Pleasantness* there were two different sound examples. The sounds were first distributed into two groups, so that each group contained sounds of all four degrees of *Pleasantness* (see table 1). Then the sounds were combined pairwise amongst the groups. For the combinations the sound pressure level of the singular sounds was not modified and the sounds were not distributed spatially. Nevertheless, each single sound was audible in all combinations. The stimuli had a length of 15 seconds each and were presented to the test participants via electrostatic headphones (STAX SR-303).

Table 1 – Two groups of quasi-stationary sounds used in the listening study

Pleasantness	Group 1	Group 2
least	lawn mower	circular saw
	playing children	air conditioner
	road traffic noise	wind chimes
highest	water sound	bird song

2.2 Test procedure

The listening test was conducted in a soundproof recording studio. After a short explanation by the instructor, the participants performed the test independently using a computer-based questionnaire. The test persons had to evaluate 24 sound examples in total, consisting of singular sounds and their pairwise combinations. The stimuli were replayed only once in randomized order and evaluated directly after listening to them. The participants were asked to rate the *Pleasantness* of the presented sound environment in the context of spending some leisure time in their own garden. Evaluations were carried out using a unipolar 100-step rating scale.

3. RESULTS

3.1 Pleasantness evaluation of single and combined sounds

As anticipated, the ratings of the single sound events reveal great differences in *Pleasantness*. Figure 1 shows the arithmetic means of single and combination ratings with 95% confidence intervals on a scale from 0 (unpleasant) to 100 (pleasant). The lawn mower (blue bars), which was the worst rated sound in group 1, received a mean *Pleasantness* rating of 16.0. This value is depicted four times for ease of comparison. The red bars represent the mean ratings of the four different sounds from group 2 (circular saw, air conditioner, wind chimes and water sound) with *Pleasantness* values from 5.8 to 73.7. The ratings of the pairwise sound combinations of the lawn mower sound with each of the sounds from group 2 are depicted in green colour.

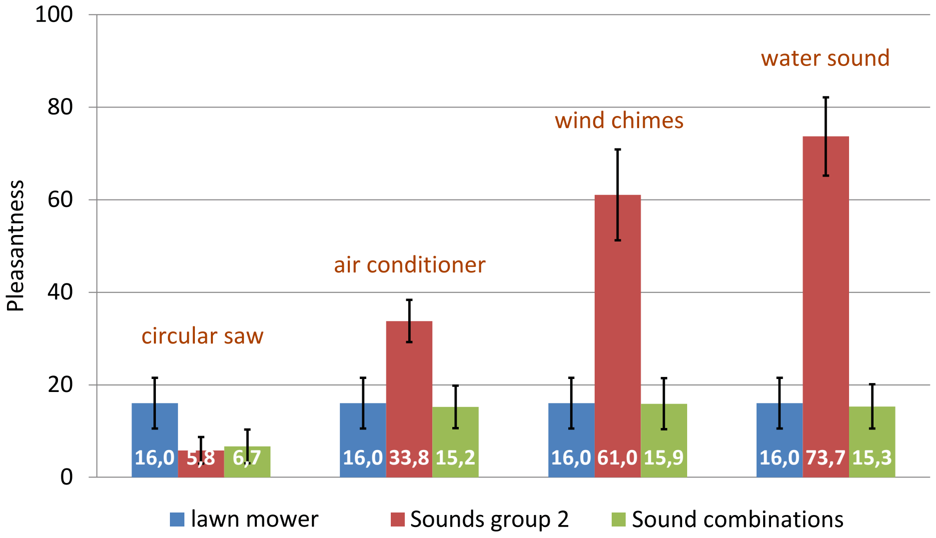

Figure 1 – *Pleasantness* ratings (arithm. means with confidence intervals ($\alpha = .05$)) of single sounds (blue, red) and their pairwise combinations (green) .

Comparing the combination ratings with the corresponding single sound ratings, it can be seen that the values of the sound combinations match the value of the least pleasant single sound in all four cases. In the first case, the sound of the circular saw received a *Pleasantness* value of 5.8 which is lower than the rating of the lawn mower. The mean value of the combination of both sounds is 6.7. In the other three cases, the lawn mower is the least pleasant sound. Although the sounds from group 2 show significantly different

Pleasantness values, the three respective combination ratings have similar mean values. In contrast, figure 2 shows that the combination of two sounds with medium *Pleasantness* values results in an overall rating between both single ratings. The combination of road traffic noise with a *Pleasantness* value of 46.8 and air conditioner sound, which received a mean value of 33.8, received an average rating of 36.2. The same applies to the combination of road traffic noise with wind chimes as well as with water sound. Moreover, the *Pleasantness* ratings of the sound combinations increase with the *Pleasantness* of the sounds from group 2. However, the results also show, as predicted, that the influence of pleasant sounds is lower than the effect of unpleasant sounds. Regarding the combination of road traffic noise with the circular saw, where the difference in *Pleasantness* is considerably high, the combination rating most notably corresponds to the *Pleasantness* rating of the circular saw.

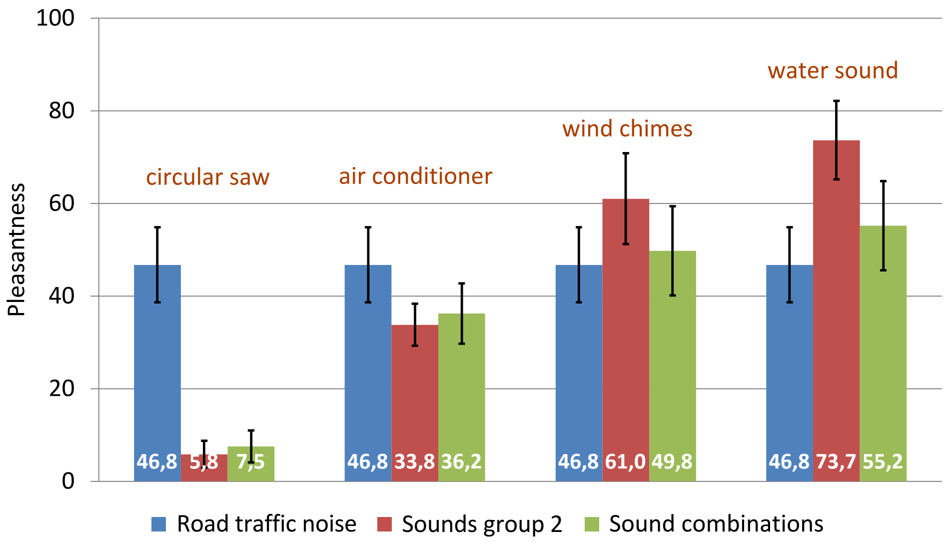

Figure 2 – *Pleasantness* ratings (arithm. means with confidence intervals ($\alpha = .05$)) of single sounds (blue, red) and their pairwise combinations (green) .

To explain the relationship between single and combination ratings, a correlation analysis with Zwicker's loudness N (ISO 532 B) was performed first. The *Pleasantness* ratings reveal a strong correlation with the single and combined sounds' loudness which is statistically highly significant as well (Pearson's correlation coefficient $r = -.94, p < .01$). In comparison, the correlation between the ratings and the A-weighted sound pressure level of the stimuli is lower ($r = -.85, p < .01$).

3.2 Regression analysis

After transforming the ratings of the single sounds to a scale ranging from -50 to $+50$ (0 = neutral *Pleasantness*) a multiple regression analysis ('enter' method in SPSS) was calculated (see table 2). The mean-centering of the ratings, which is only necessary for calculating the interaction variable, was performed in order to depict the single ratings as positive and negative contributions to the overall rating. The resulting regression model contains three statistically significant predictors ($p < .01$) for the overall evaluation of *Pleasantness* of two combined sound events: First, the two single sound ratings (standardized regression coefficients: $\beta_1 = .62, \beta_2 = .76$) and second an interaction variable consisting of the product of both single ratings ($\beta_3 = .40$).

Table 2 – Statistics of the regression model with the dependent variable 'combination rating'

Model	unstandard. B	standard error	standard. β	T	p
intercept	-12.468	1.479		-8.432	.000
sound group 1	.554	.059	.622	9.311	.000
sound group 2	.642	.055	.762	11.680	.000
interaction	.013	.002	.402	5.982	.000

The variance inflation factors ($VIF_1 = 1.06, VIF_2 = 1.01, VIF_3 = 1.07$) indicate no collinearity problems among the three predictors. With a coefficient of determination of $R^2 = .95 (p < .01, \alpha = .05)$ the regression model possesses high accuracy.

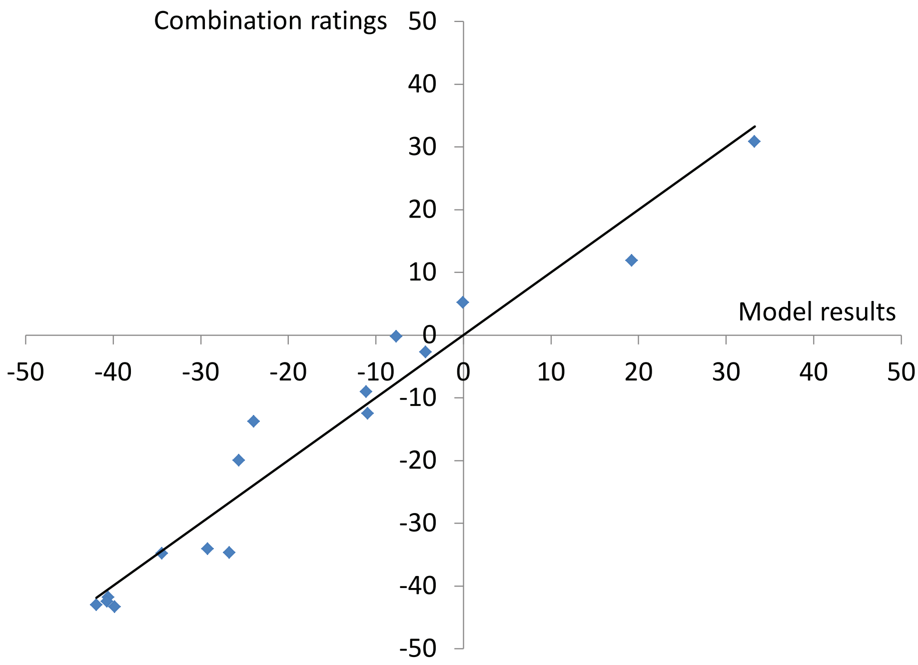

Figure 3 – Regression model for the *Pleasantness* evaluation of combined sounds.

4. DISCUSSION

The results from the listening study confirm the previously formulated hypothesis that the overall evaluation of two combined sounds can be explained by the weighted summation of the single ratings and their interaction. While a simple averaging of the single ratings without any interaction variable does not sufficiently match the combination ratings, the proposed regression model gives a better estimation. The model contains both single ratings and their product as predictors for the *Pleasantness* rating of the respective sound combination. The weighting factor for the second sound rating ($\beta_2 = .76$) is slightly higher than the beta weight for the first predictor ($\beta_1 = .62$). This is probably due to the fact that the least pleasant sound in group 2, the circular saw, received a significantly lower rating than the least pleasant sound in group 1, the lawn mower. Thus, the influence of group 2 is slightly stronger in this case. The third predictor variable, the product of both single ratings, represents the assumed interaction mechanisms between the two sounds, namely the negativity dominance and partial masking effects. The product reveals, that the contribution of one singular sound to the overall *Pleasantness* depends on the *Pleasantness* of the other sound. When combining two sounds with medium *Pleasantness*, the interaction effect is low and the combination rating is primarily determined by the first two predictors, the single ratings. In contrast, the combination of two sounds with great differences in *Pleasantness* results in a high negative interaction value, which again results in a correct prediction of a combination rating more unpleasant than the average of both single ratings.

Basically, the listening test reveals, that sounds with low *Pleasantness* ratings have a stronger influence on the overall evaluation than sounds with respective high *Pleasantness* ratings. On the one hand, this might be attributed to differences in loudness and corresponding masking effects. The high correlation of the *Pleasantness* ratings with Zwicker's loudness supports this assumption. The unpleasant sounds in this study have a higher loudness than the pleasant ones. However, it should be noted that, despite of the differences in loudness, each single sound was audible in all combinations being evaluated. Nevertheless, lawn mower noise, for instance, obviously masks a bird song or water sound to a certain degree so it appears plausible that the lawn mower sound has a decisive effect on the combination rating. The strong effect of unpleasant sounds can further be explained by the negativity dominance described before. The sound of the circular saw, for example, received the lowest *Pleasantness* rating of all sounds and dominated the evaluation, no matter which other sound it was combined with. Obviously, this kind of sound evoked a strictly negative impression in the context of this study that could not be compensated or improved by any other sound. In this case, adding a more pleasant sound did not have any effect. The situation is different, when sounds with medium *Pleasantness* are combined with more pleasant sounds. In these cases, the combination ratings were higher than the rating of the less pleasant single sound. Therefore, pleasant sounds seem to have a beneficial effect, which is in line with the results from recent studies on the positive influence of natural sounds in noisy environments. The results also show that this effect increases with the *Pleasantness* of the single sounds and the combination rating then converges to the average of both single ratings. This might be attributed to positive connotations with natural acoustical environments and also reflects experiences from everyday life. The combination of water sound and bird song creates a calm atmosphere while noise caused by people or technical devices can provoke annoyance more easily.

Two highly pleasant sounds can thus create an acoustical environment of higher value and induce a combination rating which is higher than both single ratings. The regression model also provides for such a ‘positivity bias’, although this effect was not observed in the present listening test. One reason might be the selection of sounds, as only two of the singular sounds received considerably high *Pleasantness* ratings. But also the test environment can hinder the effect of positivity bias. Sound evaluations in laboratory under purely acoustical environment are known to result in more negative judgments than respective assessments in ecologically more valid environments (13). As a consequence, we have to investigate, if it is possible to generate a positivity bias in a test environment with increased degree of reality.

One may also think, that the combination of two pleasant sounds can lead to a negative overall rating. When both single sounds contain strong tonal components that interfere with each other and generate musical consonance or dissonance, more complex interaction effects occur, that can not be explained by the existing regression model. However, concerning environmental sounds, the occurrence of such combinations in everyday life can be considered low.

Another aspect to be mentioned is the evaluation of *Pleasantness* in general. Both figures 1 and 2 reveal, that the confidence intervals of the unpleasant sounds are smaller than those of the pleasant sounds. This shows, that people agree predominantly in evaluating sounds as *unpleasant*, while the classification of a sound as being *pleasant* is more ambiguous and presumably stronger influenced by personal taste and individual experiences with the sound source.

5. CONCLUSION

Based on the *Pleasantness* ratings of singular sounds, the proposed regression model gives a very accurate prediction for the overall *Pleasantness* evaluation of simple stationary noise scenarios consisting of two sound events. To continue investigating the relationship between the assessment of single and combined sounds, this model has to be validated in the course of further experiments while gradually increasing the complexity of the noise environment by adding more sound sources. Furthermore, the model has to be expanded with regard to the effect of non-stationary sound sources and the associated modifications in attention focussing. Moving sources are more salient than stationary sources and thus attract attention in an easier way. As a result, the interaction of moving and stationary sources in a sound environment has to be explored. Beyond that, in laboratory context, when the test participants are focused solely on the acoustical stimuli, Zwicker’s loudness model explains a considerably high amount of variance. However, in a test setup with increased degree of reality, the explanatory power of the psychoacoustical loudness is expected to decrease, as additional influencing variables, like visual and other impressions occur. In this context, we further have to investigate, how non-acoustic variables influence the evaluation of a noise environment’s *Pleasantness* in detail and to what extent our regression model is still applicable.

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