TIME STRUCTURE ANALYSIS OF FAN SOUNDS

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SUMMARY

The psychoacoustic metric "roughness" is useful to evaluate time-related sound properties of fan sound with respect to its perceived quality. In a psychoacoustic analysis different algorithms for determining the metric "roughness" are in use, e.g. by Sottek, Daniel or Oetjen. Typically, for complex sounds of fans the available algorithms are insufficient to yield values of roughness which reflect the results of jury tests. In analogy to a study of Oetjen et al. we suggest and assess an improved concept of roughness for fan sound by taking into account the Shannon entropy, i.e. a parameter for the randomness of the modulation spectrum in time.

INTRODUCTION

Typically, listeners rate technical sound on a wide scale from pleasant to unpleasant. Aiming to categorize the auditive percepted sound quality, several analytical descriptions, here named (psycho)acoustic metrics such as loudness (DIN 45631/A1, ISO 532-1 [1, 2]), sharpness (DIN 45692 [3]), tonality (DIN 45681, ISO 1996-2, ECMA-74 [4, 5, 6]) and the non-standardized fluctuation strength or roughness [7] are in use. This metrics are able to replace jury test results, as shown in Fig. 1, if a high correlation between metric and jury rating on adjective scale exists.

One frequent feature of sound produced by fans and fan systems is its variation in time. "Unsteady", "rough", "moving", "irregular", "restive", "fluctuating" are used as adjectives obtained by jury tests to describe this perception [8]. So far, roughness and fluctuation strength are the only two frequently encountered candidates, which are probably suitable as metrics for those adjective scales. However, according to our experience they do not completely correlate with the subjective rating of listeners, even not the adjective scale "rough - smooth" with the metric "roughness".

In this paper we try to answer the question, why the correlation of the objective roughness with the perceived descriptor "rough - smooth" for typical sounds from fans and fan systems is weak. Furthermore, we study potential improvements of this correlation by taking into account the so called "Shannon entropy" as a metric of the randomness of the modulation spectrum in time as proposed by OETJEN et al. [9] for car engine sounds.

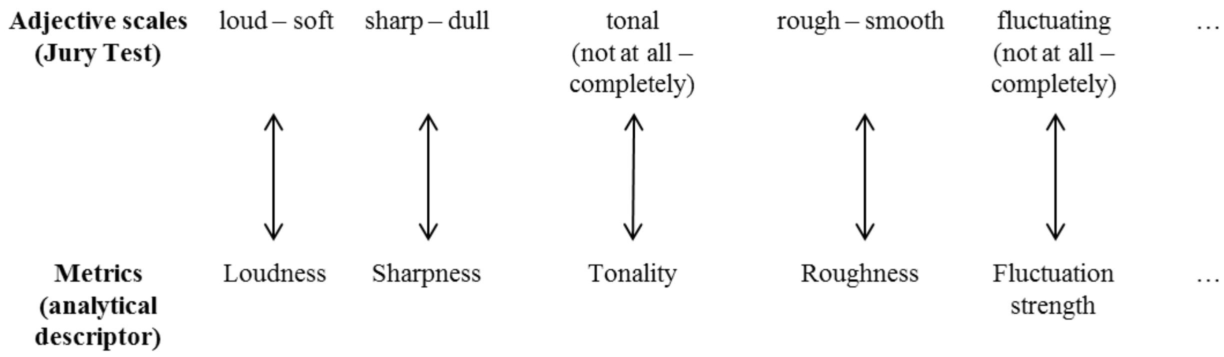

Figure 1: Relationship between the perception ascertained by adjective scales in a jury test and its analytical descriptor.

THE CONCEPTS OF ROUGHNESS AND SHANNON ENTROPY

The sensation of roughness

According to ZWICKER and FASTL [7] a sensation called roughness "is created by relatively quick changes [in amplitude or frequency] produced by modulation frequencies" above 15 Hz. While a modulation frequency below 15 Hz leads to a perception e.g. of a loudness de- and increasing in time, a frequency above this value leads to a sensation of roughness or impureness. The maximum value of roughness "1 asper" corresponds to a sinusoidal signal of carrier frequency 1 kHz, a modulation frequency of 70 Hz and a modulation degree of 1. An increase in modulation frequency above 70 Hz leads to a decrease in roughness perception and simultaneously to a growing perception of three separated tones. AURES found that an unmodulated noise could sound rough as well due to random fluctuations of its envelope, as compared to modulated tones, however, the perception of roughness is relatively low [7, 10]. Common algorithms to compute the metric "roughness" are from AURES [10], DANIEL [11], OETJEN et al. [12] and SOTTEK [13]. The algorithm developed by SOTTEK, which is based on a so called hearing model, will be used in this study.

SHANNON entropy - concept and application

The SHANNON entropy is commonly used in information theory as a metric of the randomness of a distribution. If we investigate the occurrence of modulation frequencies in a signal, we first of all assume that the sound source emits frequencies $f_{m.1}$, $f_{m.2}$, ..., $f_{m.n}$ with a probability of p_1, p_2, ..., p_n. The entropy of one distinct modulation frequency $f_{m.i}$ could be determined by

$$H_i = -\log_2 p_i \,. \qquad (1)$$

Therefore if a signal contains only one modulation frequency the probability p_i is 1 and hence the entropy is 0. Otherwise if a modulation frequency occurs only rarely in the signal the entropy reaches a high value. To compute the randomness of occurrence of a quantity of n different modulation frequencies we calculate the mean entropy defined as

$$H(X) = -\sum_{i=1}^{n} p_i \log_2 p_i \ . \qquad (2)$$

Therefore if a signal is modulated by just one modulation frequency the probability is 1. The SHANNON Entropy *H(X)* in this case would be computed to zero as the signal is not randomly modulated. If we instead compute the SHANNON entropy of a signal modulated randomly by 100 different modulation frequencies with a particular probability of 0.01 each *H(X)* reaches a value of 6.6 bit.

As the roughness is influenced only by modulation frequencies between 15 and 150 Hz [14] this study has been restrained to this range. Moreover, only dominant modulation frequencies in a very small time window are investigated. Each sound analyzed was split into several 75 % overlapping 0.2 s-long time windows in which the dominant frequency value has been considered, cp. Fig. 2. The frequency resolution of a 0.2 s-long time window is 5 Hz. Smaller time windows would not be useful as the frequency resolution would decrease [14]. The overlap has been chosen considering the time constant of the human ear which is 0.05 s, i.e. 25 % of 0.2 s [15].

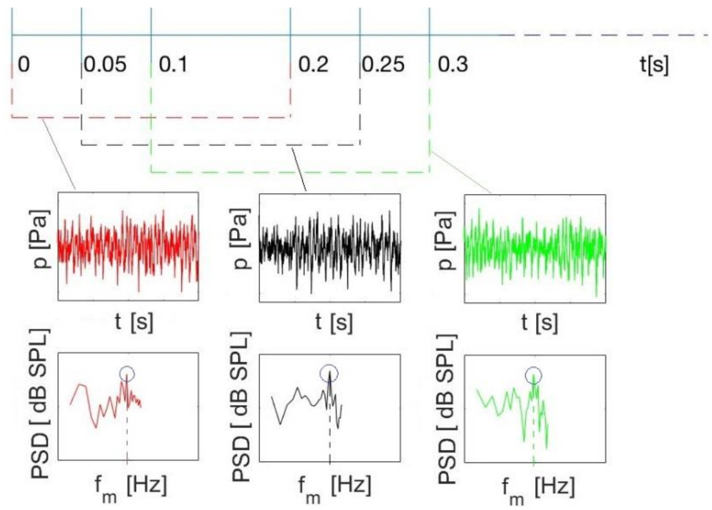

Figure 2: Time windowing for Shannon entropy computation (top), local pressure signals (middle) and local modulation spectrum (bottom).

The values of the dominant modulation frequency f_m along the whole duration of the signal were gathered forming its distribution over time for each sound. Now, the SHANNON entropy measures the probability p_i of a dominant modulation frequency f_{mi} to occur in the 10 s sequence of the sound.

Fig. 3 shows statistics and histograms of f_m over 10 s for two distinct fan sounds. A histogram with numerous bins activated denotes that the dominant modulation frequency has reached numerous values and therefore denotes a high value of the SHANNON entropy. On the contrary, a histogram with few bins activated is obtained when considering a sound with a dominant modulation frequency which does not vary much over time i.e. a sound with low SHANNON entropy.

Enhanced roughness by taking into account the SHANNON entropy

According to OETJEN et al. [9] the roughness is calculated in 0.2 s long overlapping time windows. The roughness in this time windows could be computed as very high although it contradicts the human perception. OETJEN et al. observed that the modulation frequencies in consecutive time windows can be distributed irregularly. Therefore he introduced the SHANNON entropy as weighting factor for the calculated roughness. Since a fast change in modulation frequency over time results in a lack of roughness sensation he came up with this correction equation:

$$R_{corr} = \frac{R}{(\alpha + H)^{\beta}} \tag{3}$$

where H is the SHANNON entropy and α and β are parameters to be determined by jury test ratings.

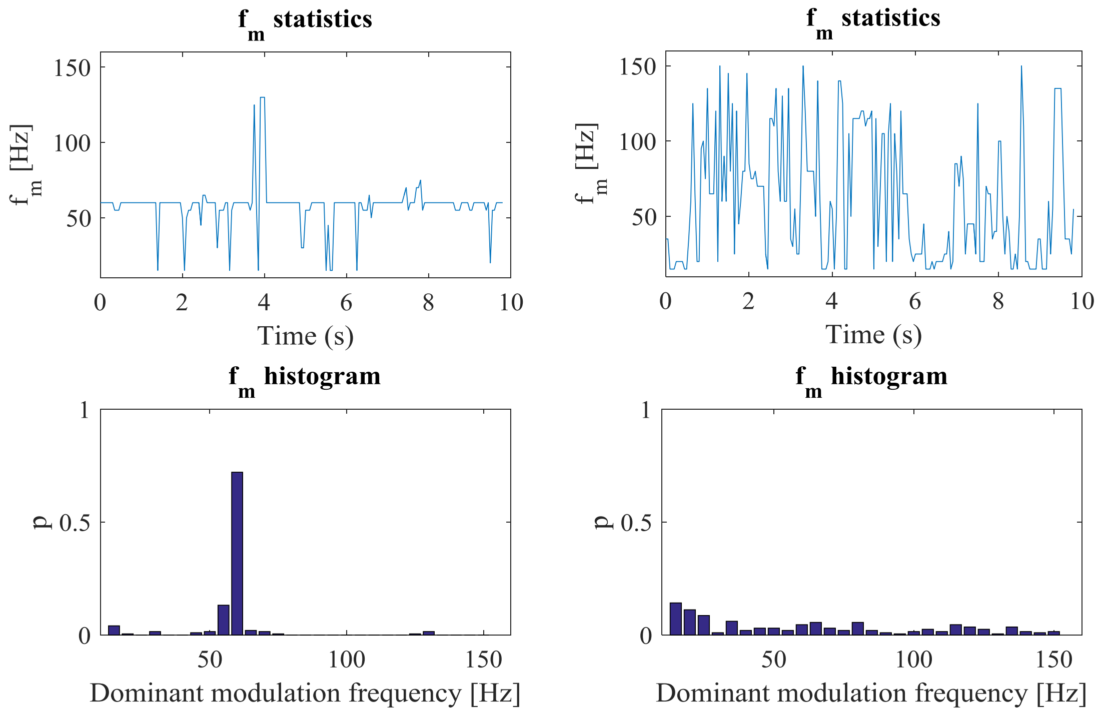

Figure 3: Statistics and histogram of f_m over 10 s of two exemplary fan sound with a low f_m distribution randomness on the left (H = 1.58 bit) and a high f_m distribution randomness on the right (H = 4.35 bit) .

JURY TESTS

We assume that the roughness sensation is not only affected by modulation parameters but also by the loudness and the sharpness of a sound. Therefore, in order to eliminate factors independent from the time describing parameters, the loudness for all sounds used in jury tests was set to 10 sone. From a huge data base of fan sounds in total eleven were selected, with a minimum variation of sharpness but a maximum variation of roughness and SHANNON entropy. As the roughness metric according to SOTTEK provides good roughness estimates for simply modulated sounds, we decided to add four artificial sounds, i.e. sinusoidal signals with roughness values between 0.03 and 0.09 asper, a range that is typical for fan sounds with a loudness of 10 sone. To achieve this range, the modulation frequency f_m ranged from 17 to 70 Hz and the modulation degree m ranged from 0.3 to 0.5. The carrier frequency f_c was set to 160 Hz for the four artificial sounds.

Prior to the test the 24 participants (15 m/9 w) of average age of 25 years were instructed in written form. The jury test persons were confronted with a graphical user interface shown in Fig 5, realized in MATLAB®. The sounds were presented via Sennheiser HD 650 headphones and a RME Fireface UC soundcard. The test started with a familiarization to the adjective pair "rough - smooth" via different artificial sound samples, composed of (un-)modulated tones in a broadband noise. To illustrate the perceptions "smooth", "a little bit rough", "rough" and "fluctuating, not rough" the tone components of the signals were modulated with f_m = 0 Hz, 30 Hz, 60 Hz and 4 Hz. The participants could listen to this exemplary sounds as often as necessary. In a verification step the participants had to rate subsequent to the familiarization three fan sounds if they sound rough or not by just answering with yes or no on the screen. Later on these results were used to test the participant reliability. Eventually, the participants had to classify the eleven fan and four artificial sounds not used in the steps before in the main test on a continuous scale from "smooth" to "rough". In order to avoid any kind of dependency of the results on the order of occurrence of the sounds, they were sorted randomly for each participant. Moreover, each jury test person was permitted to change the displayed order of sounds after their first evaluation by clicking on "Sort" all time to allow an easy comparison of similar perceived sounds.

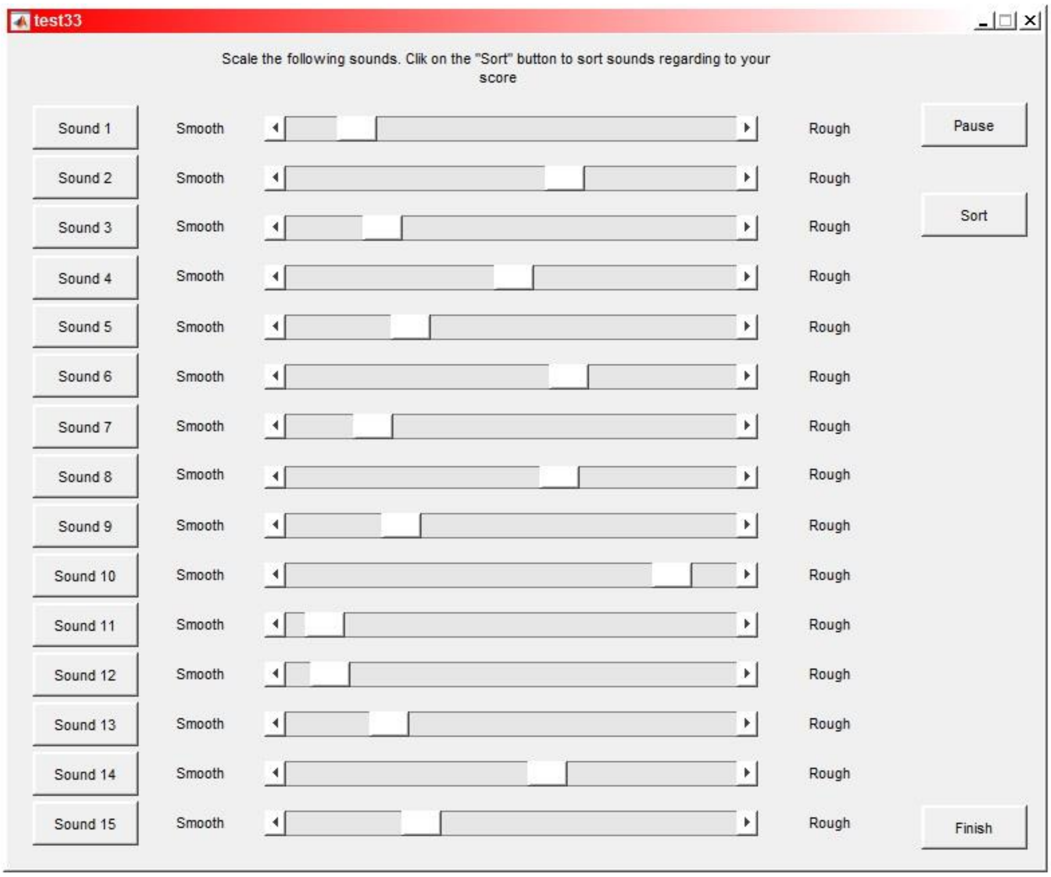

Figure 4: GUI used in the listening test for roughness evaluation. On the left side of the interface the jury test person starts a sound. He or she had the possibility to pause all the time as well as to sort the sounds by their ratings.

The scale displayed by a continuous slider ranged from zero ("smooth") to one ("rough"). If a particular participant did not use the whole scale over all sounds, e.g. his minimum evaluation is 0.3 and his maximum 0.8, the evaluation was stretched to a range from 0 to 1 for a better inter-individual comparison. In addition the test results were transformed on a roughness scale in asper with the aim of minimizing the error between the rating and the computation of roughness of the four artificial sounds.

RESULTS

One participant rated totally different as all others. The rating from this participant was excluded. With a cluster analysis, cp. BORTZ and DÖRING [16], two participant groups were identified. By comparing these two participant group ratings in Fig. 5 over the computed roughness it became obvious that their comprehension of roughness is contrary. However this different understanding was not visible in the verification step. Based on the objective metric "roughness" one expects that most of the fan sounds chosen for the test are rated smoother than the reference since an irregular distribution of modulation frequencies would reduce the roughness sensation. That means that the first participant group, shown in Figure 5 (left) seems to rate according to the established definition of roughness, while the second group, cp. Figure 5 (right), although it contains almost two third of the participants, measures something else. Since we aim at optimizing the roughness metric we focus on the first participant group, which acts according to the definition, and derive a correction only for the data from this group.

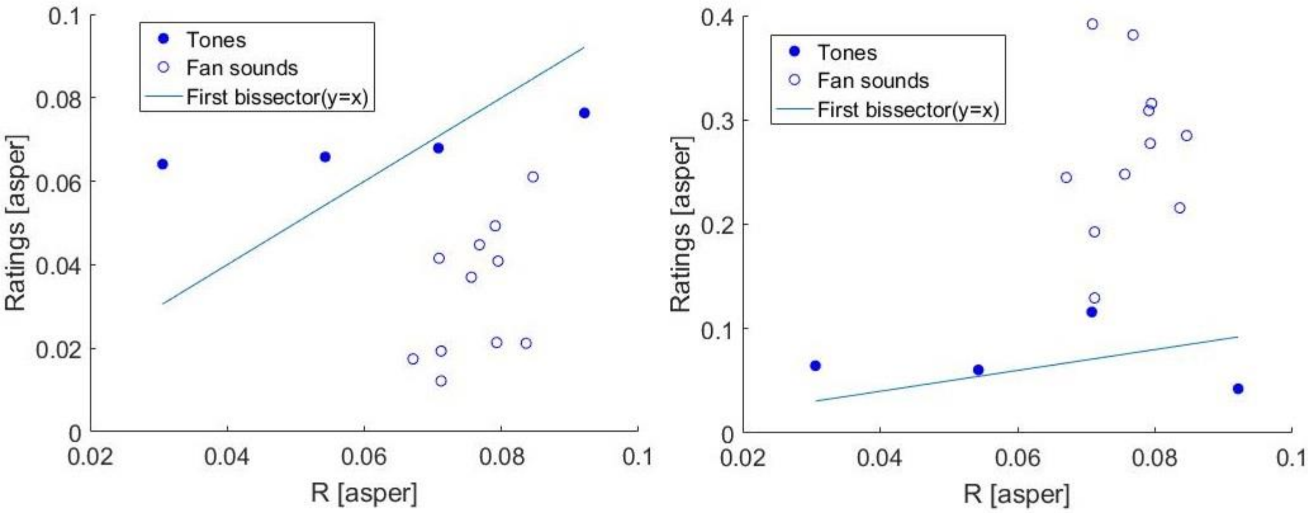

Figure 5: Ratings of the first participant group (left) and the second group (right) estimated in asper versus the computed roughness. Reference sounds are represented with filled, fan sounds with blank dots.

CORRECTION VIA THE SHANNON ENTROPY ACCORDING TO OETJEN

The fan sound roughness values, represented by blank dots in Fig. 5 (left), are overestimated by the roughness metric used, as the randomness in f_m - distribution should lead to lower roughness values in comparison to the artificial sounds with their single f_m and hence non-existent randomness. As shown by OETJEN et. al [9] an overestimation could be due to the fact of high randomness of modulation frequencies in the signal. The aim is to find the best coefficients α and β in the ansatz eq. (3) to minimize the error between the ratings and the corrected roughness metric. For the participant group measuring correctly the roughness the minimum value of the error between ratings and computed roughness has been obtained while considering $\alpha = 1$ and $\beta = 0.80$. Fig. 6 compares the subjective ratings against the estimated roughness values with correction (red marks) and without correction (blue marks).

The correction shows a huge improvement for the estimated roughness. Therefore, the model by OETJEN et. al is useful for fan sounds with a random distribution of occurred modulation frequencies as long as the participants are able to comprehend roughness in line with the literature.

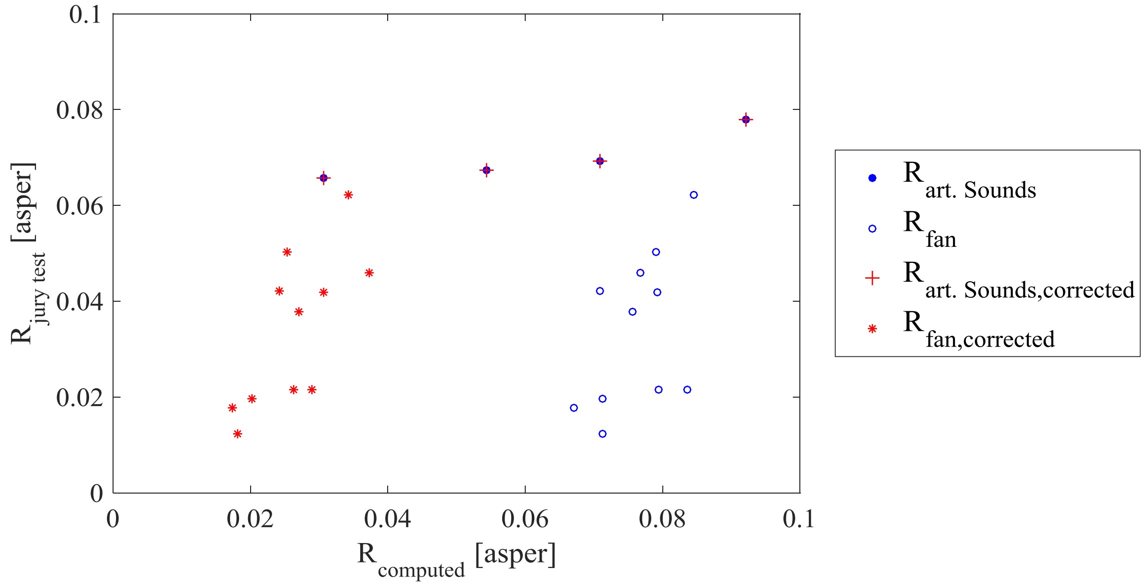

Figure 6: Subjective ratings against the roughness metric with and without correction. The corrected values are represented in red, the uncorrected values are represented in blue.

SUMMARY AND CONCLUSION

In this paper we investigated the relationship between an analytical descriptor of the acoustic sensation of roughness and the perception evaluated on the scale "rough - smooth" for different fans and fan systems. It could be demonstrated that the common metric, which was originally constructed by using artificial sounds, could not represent the roughness sensation of fan sounds. Although all participants were primed with the same artificial sounds on the definition of roughness, the results show two distinct participant groups who evaluated contrary on the roughness scale. Despite not failing in a preceding verification step, the groups seem to have a different interpretation of the roughness sensation. It is supposed that the second participant group is influenced by the tone-to-noise ratio, i.e. the more present a broad band noise is in a sound the rougher it is perceived. Therefore this group would in fact not measure the roughness by its definition.

An already studied correction by using the SHANNON entropy, here used to measure the randomness of occurrence of modulation frequencies in the signal, improves the estimation of roughness for the first participant group. The overestimation of the roughness metric by SOTTEK could be corrected by taking into account the random modulation in the complex fan sound which is evoked by the unmodulated broad band noise as well as by modulated tone components. Although the correction model is useful for one of the participant groups, the majority measures a different character in the sound, which they would call a "rough" sensation. As the definition of roughness is discussed by acoustic experts as well, it is desirable to search for adjective scales which are clearly more related to the observed time structure of fan sounds for all participants.

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