ISCA Archive
http://www.isca-speech.org/archive

First ISCA ITRW on
Auditory Quality of Systems
Akademie Mont-Cenis, Germany
April 23-25, 2003

The Effect of Attenuation Rate and Peak Bandwidth of Tonal Components on Perceived Tonalness

Aaron Hastings, Patricia Davies

The Ray W. Herrick Laboratories
School of Mechanical Engineering
Purdue University
`hastinga@purdue.edu, daviesp@purdue.edu`

Abstract

Band-pass filtered noise can be perceived to some degree as tonal. The perceived strength of this tonal quality depends on the spectral shape of the filtered noise and the presence of other features in the total sound. The spectral shape of bandpass filtered noise can be characterized by the center frequency, bandwidth, and roll-off rate of the filter. In order to determine the interaction between bandwidth and roll-off rate for band-pass filtered noise, the tonalness of band-pass filtered noise was evaluated by using three test methods: paired comparison, direct scaling, and an adaptive forced choice method. All three test methods yielded very similar results. Trapezoidal band-pass filtered random noise was used for the experiments. For a roll-off rate of 300 dB per octave, the tonalness of the sounds ranged from 30 to 90 percent of a pure tone's tonalness for a bandwidth of 300 to 1 percent of the critical bandwidth. For a roll-off rate of 100 dB per octave, the tonalness of the sounds ranged from 30 to 60 percent of a pure tone's tonalness. As the roll-off rate of the filtered sounds approached zero, the tonalness disappears.

1. Introduction

The presence of tonal components in a sound strongly affects the perceived sound quality. The character of the tonal component is affected by its spectral shape, other components in the signal and temporal characteristics [1, 2, 3, 4]. Tonal components can be associated with the standard sound of a product, for example, the beep of an alarm clock or the hum of a clothes washer's spin cycle. The presence of tonal components in a sound can also be annoying, for example, the tonal sound generated by tires running over pavement with evenly spaced ridges. Quantification of the change in sound quality due to the presence of unwanted tonal components typically has been addressed by applying a penalty to a level-based metric such as A-weighted sound pressure level or by using a sound quality model that is a function of metrics including one or more that quantify the sound's tonal character [5, 6, 7], however, the usefulness of either method is limited by the accuracy in predicting a sound's tonal character. A better understanding of how tonal components are perceived can be used to help designers improve product sound quality.

Sounds that are perceived as having a tonal quality include: pure tones, complex tones (including frequency and amplitude modulated tones), peaked ripple noise (noise generated by using a feedback loop to add delayed attenuated versions of the noise), high- low- and band-pass filtered noise, and comb-filtered noise [8]. Because band-pass filters can be used to generate sounds that go from white noise to (nearly) pure tones, band-pass filtered noise was used in the research described in this paper.

Tonal components with center frequencies from around 700 to 3000 Hz are perceived as more tonal than components centered at higher or lower frequencies [1, 8, 9, 10]. As the bandwidth decreases, the tonalness increases [1, 2, 3, 4]. The tonalness of low-pass filtered noise increases as the filter roll-off becomes steeper, but this effect saturates when the masking pattern of the sound ceases to increase. For example, this saturation occurs for 8 sone low-pass filtered noise with a cut-off frequency of 1000 Hz when the roll-off rate is greater than 36 dB per octave [8]. Because low-pass filtered noise is a special case of band-pass filtered noise, it is expected that the perception of the tonalness of band-pass filtered noise should exhibit a similar saturation. However, since the masking pattern is asymmetric, it is not clear if the roll-off rate at which saturation occurs would be controlled by the upper or lower frequency roll-off of the masking pattern.

The roll-off rate may affect the tonal quality of a sound in another way. Noise that is band-pass filtered by using a filter with a shallow roll-off rate will have a much broader base bandwidth than peak bandwidth (see Figure 1). This may lead to a decrease in the perceived strength of the tonal character and an increase in the perceived strength of the noise character of a sound. Because both bandwidth and roll-off rate affect the tonal quality and these two factors are interrelated, the two factors should be considered simultaneously when modelling the tonal quality of band-pass filtered sounds.

Random noise was band-pass filtered by using trapezoidal filters with peak bandwidths from 1 to 300% of the critical bandwidth and with attenuation rates from 0 to 300 dB per octave. The sounds were then evaluated for their tonalness by using three test methods: direct scaling, paired comparison, and an adaptive forced choice method. In order to evaluate the effect of bandwidth and roll-off rate in detail, a direct scaling method was used where a value of 2 was assigned to sounds with no tonal quality (white noise) and a value of 8 was assigned to sounds with the most tonal quality (a pure tone). The paired comparison method was used because it is more reliable for naive subjects than direct scaling and thus could be used to verify the direct scaling results, however, paired comparison experiments are not practical for large sets of sounds, so only a subset of the direct scaling experiment's sounds was used in the paired comparison experiment. Both of these test methods allow the sounds to be scaled relative to each other. In order to relate the sounds to an easily measured physical parameter, an adaptive forced choice test was conducted where the the reference sounds were tonal components in broadband noise with

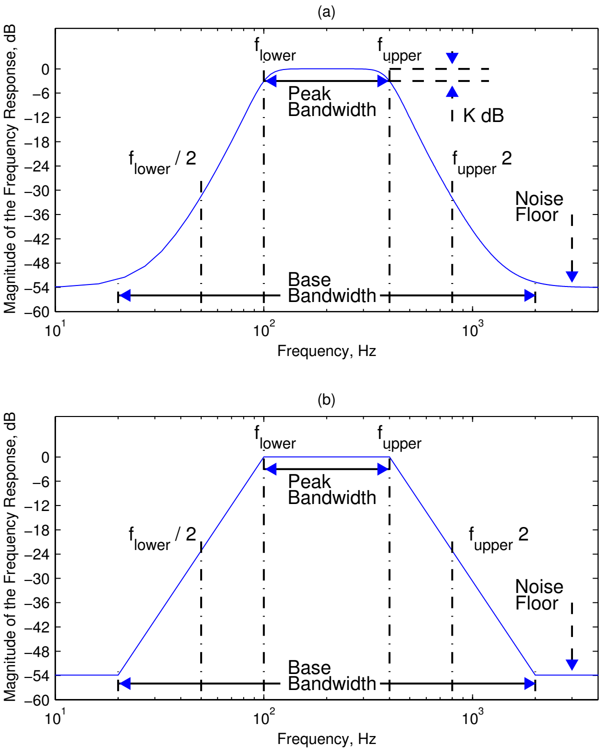

Figure 1: *Illustration of the frequency response magnitude of (a) Butterworth and (b) trapezoidal filter. In (a), the peak bandwidth is defined by where the level drops by K dB. Upper roll-offs are determined by the distance from the upper cut-off frequency, f_{upper}. Lower roll-offs are determined by distance from the lower cut-off frequency, f_{lower}.*

different signal-to-noise ratios.

2. Test Sounds

In previous experiments, 4^{th} and 6^{th} order Butterworth filters had been used to filter random noise in order to generate tonal components for subjective evaluation [9]. Bandwidth was defined for the components by the one-half power (3 dB down) points. In order to have a finer control over the roll-off rate and "bandwidth", finite impulse response (FIR) trapezoidal digital filters were used to filter digitally generated gaussian distributed white noise. Peak bandwidth here is defined as the width of the region of the trapezoidal filter frequency response that has a gain of 1, as shown in Figure 1 (b).

The trapezoidal filters were designed by specifying the cut-off frequencies and the roll-off rate. The cut-off frequencies were chosen so that the peak bandwidth would be a percent of the critical bandwidth (CBW) centered at 700 Hz, where $CBW = 24.7(4.37f_c/1000 + 1)$ and f_c is 700 Hz [11]. The roll-off was controlled by specifying the attenuation at 2.5 Hz increments below and above the cut-off frequencies. The attenuation was increased by N dB per octave, where N was the desired roll-off. A sampling frequency (f_s) of 22050 Hz was chosen. In keeping with digital filter design practice [12], conjugate symmetry was imposed around $f_s/2$. The frequency responses of the resulting digital filters were checked to ensure that the filters met the specifications at frequencies in between those specified in the designs. An example showing the detail around the lower cut-off frequency is shown in Figure 2. A set of filters was designed with the peak bandwidth and roll-off rates shown in Table 1.

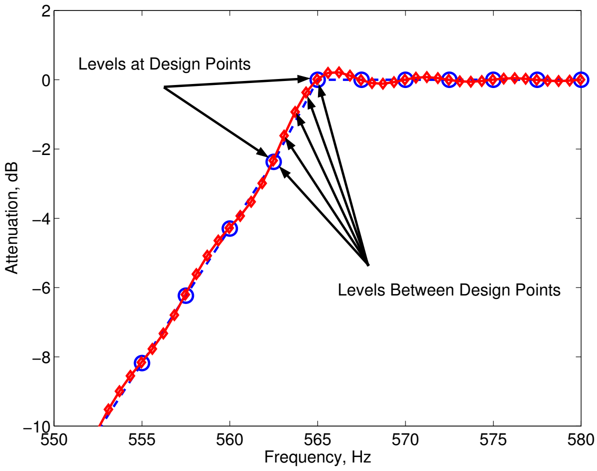

Figure 2: *Detail of frequency response magnitude between the designed points.* ○ *- designed points* ◇ *- points estimated by zero padding the impulse response.*

The filters were used to filter 20 seconds of random noise sampled at 22050 Hz. Each sound was then normalized to a loudness of 16 sones for a diffuse field according to ISO 532B. It was desired to play the sounds for a much shorter length during the experiment, so the middle 2.5 seconds of each sound was used. This ensured that there were no ringing effects, due to the transient response of the FIR filters, present in the test sound. In addition to the filtered noise, a pure tone signal and white noise were added to the set of sounds. Twenty milli-second cosine ramps were also applied to the beginning and end of each sound to prevent "clicks" during playback.

Table 1: *Roll-off rate and peak bandwidth of filters used to generate the experiment sounds. All filters are centered at 700 Hz. A "✓" indicates that the filter parameters were used in the direct scaling test. A "+" indicates that the filter parameters were used in the paired comparison test.*

	Roll-Off Rate, dB / Octave								
% CBW	5	20	40	60	80	100	150	200	300
1	✓	✓+	✓+	✓+	✓+	✓+	✓	✓	✓+
10									✓
20		✓	✓	✓	✓	✓	✓	✓	✓
30									✓
40				✓	✓	✓+	✓	✓	✓+
70								✓	✓
100				✓	✓	✓+	✓+	✓+	✓+
150								✓	✓
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
300								✓	✓

For each experiment, the subjects, fitted with Etymotic Research ER-2 calibrated earphones, sat at table with a computer keyboard and monitor in a sound isolated booth. The sounds were played from a computer outside the sound booth by using a LynxONE sound card connected to a Tucker-Davis Technologies HB7 headphone amplifier. The system was calibrated such that the measured sound pressure level of a 90 dB sine wave played through the earphones connected to a sound level meter by using a Zwislocki coupler would be 90 dB.

3. Experiment 1: Direct Scaling Test

It was desired to determine the effect of the trapezoidal filter's peak bandwidth and roll-off rate on the perception of tonalness. Sounds were chosen that ranged from purely tonal to completely noisy in fine increments. The resulting 48 sounds included white noise, a pure tone, and the 46 filtered noise sounds.

The subjects for this experiment were recruited at Purdue University. Their ages ranged from 20 to 33 years of age. This group was culturally diverse and included American, Korean, Chinese, Japanese, Mexican, Columbian, Turkish, and Indian students. There were 8 females and 16 males in the group. Two persons were rejected from the group, one who failed a hearing test and one who did not follow the directions during the testing. The remaining 22 subjects participated in this direct scaling test and in the paired comparison test described later. These two tests were completed by each subject in a 1 hour session. The order of the experiments was randomized with half doing the paired comparison test first and the other half doing the direct scaling experiment first.

3.1. Procedure

Prior to each subject's arrival, the playback system was calibrated and all unnecessary sound sources near to the sound booth were turned off. The subjects were then brought to the sound booth where they read and signed a consent form which had been approved by Purdue University's Committee on the Use of Human Research Subjects. The subjects then filled out a questionnaire regarding their background and noise exposure and evaluation experience. The subject's hearing was tested and a subject failed this test if their threshold was more than 20 dB above the normal threshold for pure tones at 125, 250, 500, 750, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. If the hearing test was passed, test instructions were given to the subjects describing tonal and non-tonal signals by using examples of non-tonal sounds (white noise) and tonal sounds (a pure tone). For the direct scaling experiment, the subjects were asked to give a rating of 2 to sounds that were not at all tonal and a rating of 8 to sounds that were the most tonal. Before the test, the subjects played a subset of 18 test sounds to familiarize themselves with the range of sounds that would be in the test. The subjects were encouraged to play these sounds as often as they needed to help them maintain their internal scale of tonalness. Once the subjects were familiar with the sounds, they went through a practice test to get used to the testing format. They then took the test. The sounds were presented in a random order for each subject. While they were taking the test, the sounds and the subject responses were remotely observed to make sure that the sounds were being played correctly and to make sure that the subjects were not reversing the scale. After the experiment, the subjects were asked for any comments or observations about the test and were paid $10 for participating in the test.

3.2. Analysis and Results

The responses of 22 subjects were averaged to obtain an estimate for the tonalness of each sound. In order to more easily compare the tonalness estimates from the different experiments, the tonalness estimates were rescaled so that noise had a value of 0 and the pure tone at 700 Hz had a tonalness of 1. In this way one can think of the tonalness score as a fraction of that which would be obtained for a pure tone of the same frequency and loudness. The results are shown in Figure 3 as circles (◯). The tonalness for all the sounds having a peak bandwidth of 1% are connected by a dashed (— —) line, similarly, the sounds having a peak bandwidth of 200% are connected by a dotted (· · ·) line. Tonalness variation due to changes in the peak bandwidth are shown in Figure 4 for band-limited noise generated by using filters with roll-off rates from 5 to 300 dB per octave.

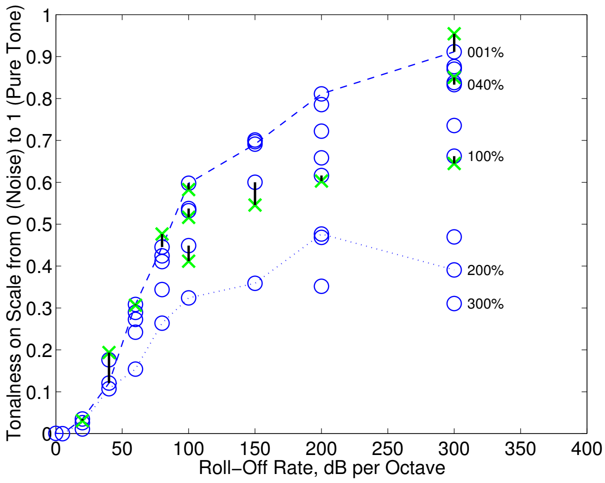

Figure 3: *Tonalness of band-passed noise as a function of roll-off rate. The ◯ are the results for the direct scaling experiment. The dashed (- -) line connects sounds whose peak bandwidth was 1% of the critical bandwidth. The dotted (···) line connects sounds whose peak bandwidth was 200% of the critical bandwidth. The × are the results for the paired comparison test.*

As the roll-off rate increases, the range of tonalness due to changes in peak bandwidth increases. It can be seen in both Figures 3 and 4 that for low roll-off rates, even the sounds with the narrowest peak bandwidth are not judged to have any appreciable tonalness. For high roll-off rates, the peak bandwidth becomes much more important. For the sounds with roll-off rates of 300 dB per octave, the tonalness triples as the peak bandwidth decreases from 300 to 1% of the critical bandwidth (see Figure 4). Finally, even for the widest bandwidths tested at high roll-off rates, the tonalness is around 30 to 40% of the tonalness of a pure tone. This tonalness can be attributed to the roll-off at the cut-off frequency, the effect described by Fastl for low-pass noise [8], however the saturation occurs for a roll-off rate of around 100 dB per octave for the widest band-pass noises considered in this experiment compared to the 36 dB per octave for low-pass noise that Fastl describes.

4. Experiment 2: Paired Comparison Test

Exposure to a very strong or weak sensation can cause a subject's internal scale to shift. To some extent, these effects are reduced by averaging the responses from subjects who heard the sounds in different orders, however, this internal scale shift can still be a problem for direct scaling experiments. If the internal scale used to make judgements is not stable, then the direct scaling from one test sound to the next may not represent the true sensation difference. With paired comparisons, the task is reduced to a discrimination, for example "Which signal has the

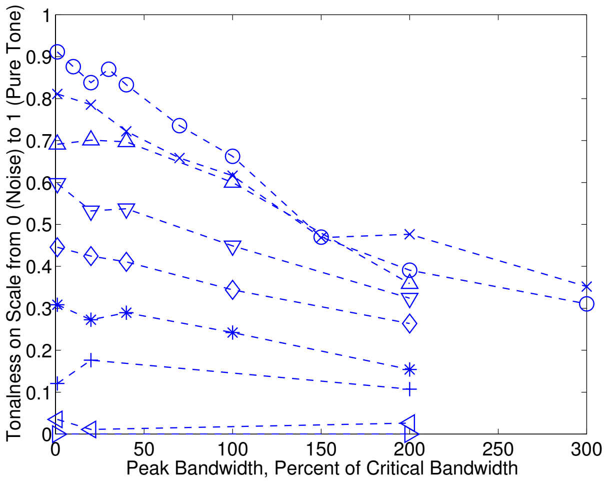

Figure 4: *Tonalness of band-limited noise as a function peak bandwidth. Roll-off rates of: 300 (○), 200 (×), 150 (△), 100 (▽), 80 (◇), 60 (∗), 40 (+), 20 (◁), and 5 (▷) dB per octave.*

sensation?" or "Which signal has a stronger sensation?" For naive subjects this task is easier than assigning the numbers in the direct scaling experiment. A paired comparison test was conducted to check that the direct scaling test results were reliable.

The sounds used for the paired comparison test were a subset of those used in the direct scaling test. The filter characteristics used to generate the sounds are indicated in Table 1 by a "+". The sounds chosen either had roll-off rates near 100 dB per octave; had peak bandwidths that were one critical bandwidth wide; or where from the least tonal and most tonal band-pass sounds. All sound pair combinations were randomly played to the subjects, in both A-B and B-A order for a total of 132 paired comparisons per subject. For each pair, the subjects were asked to "choose the sound that is more tonal". The test sound playback and subject's responses were monitored remotely during the test to make sure that there were no problems with the playback and to make sure that the subjects understood the instructions.

4.1. Analysis and Results

The tonalness of the sounds was estimated by using the Bradley-Terry-Luce model [13]. The tonal sensation was modelled as $V_i = log(\pi_i)$, where π_i is determined such that it maximizes the likelihood function

$$L = \prod_i \pi_i^{a_i} \Big/ \prod_{i<j} (\pi_i + \pi_j)^{n_{ij}} \qquad (1)$$

where $a_i = \sum_{j \neq i} a_{ij}$, a_{ij} is the number of times sound i was chosen to be more tonal than sound j, and n_{ij} is the number of times that the two sounds were compared. An estimate of π_i that will maximize L is determined iteratively by using Equations (2) and (3).

$$\hat{\pi}_i^{(k)} = \hat{\pi}_i^{*(k)} \Big/ \sum_i \hat{\pi}_i^{*(k)}, \qquad (2)$$

$$\hat{\pi}_i^{*(k)} = a_i \Big/ \sum_{j \neq i} \left[n_{ij} / \left(\hat{\pi}_i^{(k-1)} + \hat{\pi}_j^{(k-1)} \right) \right], \; k = 1, 2, \ldots \qquad (3)$$

In order to compare the paired comparison results with the direct scaling results, the paired comparison results were rescaled by using a first order least squares fit to minimize the average error in $y_i = \beta + \alpha x_i + \epsilon_i$, where y is the estimated tonalness from the direct scaling experiment, x is the estimated tonalness from the paired comparison experiment, and i is the sound number. The rescaled tonalness results for the paired comparison experiment are shown as $\times$'s in Figure 3. The solid vertical lines (|) in Figure 3 link the tonalness results of a given sound for the paired comparison and direct scaling experiments. For sound i, ϵ_i is the disagreement between the results of the two experiments after rescaling. The close agreement between the two experiments supports the validity of the tonalness ratings obtained from the direct scaling experiment.

5. Experiment 3: Adaptive Forced Choice Test

The previous two experiments were conducted to determine the relationship between the tonalness of the sounds used in the test. It was also desired to relate the tonalness of the test sounds to the tonalness of a simpler sound: a pure tone in noise. The level of the noise relative to the tone can be adjusted to vary the tonalness of the simpler sound, and the tonalness of these types of sounds have been shown to be a simple function of the signal-to-noise ratio [10].

In this experiment, subjects were asked to pick a reference sound that was deemed to have a tonalness equivalent to a test sound's tonalness. The reference sound was a combination of a tonal component and broadband white noise. When adjusted, the signal-to-noise ratio of the tonal component in the broadband noise changed, however, the loudness of the reference sound was always 8 sones. In this way, the tonalness of the test sound was related to a physically measurable quantity, namely the signal-to-noise ratio of the reference sound. Vormann, Verhey, Mellert, and Schick [3] conducted a similar experiment for: harmonic and inharmonic tone complexes, narrow band noise at different bandwidths, amplitude and frequency modulated sinusoids, and for tones at different center frequencies. They used a pure tone starting at 45 dB in a uniformly exciting noise floor of 50 dB for their reference sound. Vormann et al. used an adaptive procedure whereby the tone's level was adjusted by 8 dB until the reference sound was found to be more tonal than the reference sound (a reversal). The step size was halved each time a reversal occurred until a minimum step size of 2 dB was reached. The question that the subjects were asked in Vormann et al.'s experiment was "Which signal is more tonal (tonhaltiger)?"

In this experiment, the reference sounds were 700 Hz pure tones in white noise and the test sounds were trapezoidal filtered random noise. The starting step size was 16 dB which was halved after every reversal until a minimum step size of 1 dB was obtained. The test ended after either the reference sound had been adjusted 30 times, or 10 reversals occurred. A typical converged response for a subject doing this test is shown in Figure 5. An example of a test that did not converge is shown in Figure 6. The subjects were asked to "choose which sound is more tonal." The signal-to-noise ratio of the last 5 reference signals were averaged and this was considered a measure of the test sound's tonalness.

The test sounds were chosen to be a subset of the paired

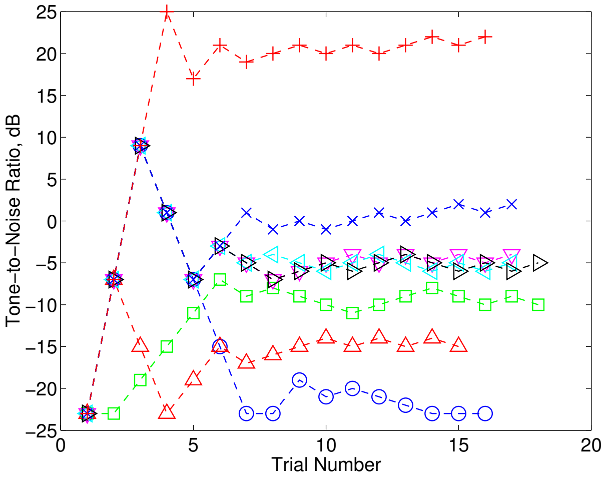

Figure 5: *Example of a typical adaptive forced choice test where the subject's responses converged. The test sounds were generated by using filters with roll-off rates (dB per octave) / peak bandwidths (% CBW) of: 20 / 1 (◯), 60 / 1 (□), 100 / 100 (△), 100 / 1 (▽), 150 / 100 (◁), 200 / 100 (▷), 300 / 100 (×), 300 / 1 (+).*

comparison test so that all three experiments could be compared. These sounds were also normalized to a Loudness of 8 sones. The filter parameters for the 8 sounds used in the test are given in Table 2. The sound booth and playback system were prepared as in the two previous experiments. Five subjects with experience in taking psychoacoustic tests participated in this experiment. They ranged in age from 22 to 33 years of age. There were 4 males and 1 female. Test sounds were evaluated in a different random order for each subject.

Table 2: *Roll-off rate and peak bandwidth of filters used to generate the sounds for the alternative forced choice test. All filters are centered at 700 Hz.*

	Roll-Off Rate, dB per Octave					
Perc. CBW	20	60	100	150	200	300
1	✓	✓	✓			✓
100			✓	✓	✓	✓

5.1. Results and Analysis

Using the adaptive forced choice method to evaluate the tonalness of band-pass filtered noise in reference to a pure tone in noise was found to be difficult. This was because the test sounds and the reference sounds had a different tonal character. The test sounds appear to have more than one perceptual attribute that affects tonalness, whereas the reference sounds may only have one attribute that affects the tonality. The tonalness of the reference sounds increased as the level of the tone increased relative to the noise. As the bandwidth of the filtered noise got narrower and the roll-off larger the sound also acquired noticeable nonstationary frequency and amplitude characteristics. To avoid switching attention between these different attributes, the subject must be very familiar with the attributes prior to taking part in the test, so that they can concentrate on one particular attribute during the test.

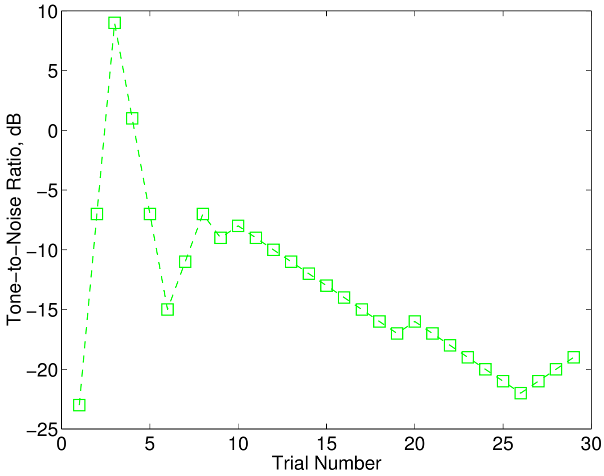

Figure 6: *Example of an adaptive forced choice test where the subject's responses did not converged. The test sound was band-passed noise filtered by a filter with a roll-off rate of 60 dB per octave and a peak bandwidth of 1% of the critical bandwidth.*

In order to try to make the comparisons easier, the pure tone in the reference sound was replaced with a frequency modulated tone and with band-pass filtered noise (300 dB per octave roll-off, 1% of critical bandwidth peak bandwidth). Although both of these reference sounds were more similar to the band-pass filtered noise of the test sounds, the results from preliminary tests were not any closer to the direct scaling and paired comparison results than the results when using the pure tone in the reference sounds.

One subject's results were not consistent with the others and was removed from the analysis. The results for the remaining subjects are shown in Figure 7 as ×'s with dashed lines (- -) connecting the results for each subject. The average of the 4 subjects' responses for each test sound is shown with a circle (◯) in Figure 7. The relative level differences between the test sounds appear to be very similar to the relative differences between tonalness for the same test sounds in the direct scaling and paired comparison experiments. In order to try to put all experiments on the same scale, Aures's metric of tonality was used to determine the tonalness of the reference sounds that were chosen as having the same tonalness as the test sounds. When this was done, the maximum value was only 0.46, so the Aures tonality values were rescaled in a manner similar to that used in the rescaling of the paired comparison values. The rescaled values of Aures's tonality for the chosen reference sounds, the rescaled paired comparison experimental results, and the rescaled direct scaling experimental results are shown in Figure 8. There is strong agreement between the three tonalness estimates, however, it was also found that a simple linear rescaling of the signal-to-noise ratio levels matched the paired comparison and direct scaling results better than the rescaled Aures tonality results.

6. Comments on Results

Three experimental methods were used to evaluate the tonal quality of trapezoidal filtered random noise. The sounds were characterized by the filter roll-off rates and peak bandwidths.

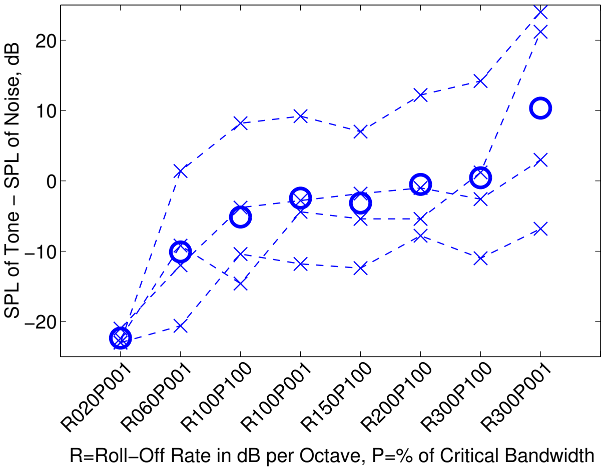

Figure 7: *Signal-to-noise ratios for the tone-in-noise reference sounds that were required in order to be perceived as having the same tonalness as the test sound.*

When the results from the three experiments were compared, the ratings of the sounds that were common to all experiments were in close agreement. This gives support to the use of the direct scaling method when evaluating many sounds, tests which would take too long if the other methods were used.

At low roll-off rates, peak bandwidth of the trapezoidal filter used to generate the test sounds does not have a strong effect on tonalness. At high roll-off rates, peak bandwidth of the trapezoidal filter strongly affects the tonalness of the sounds. The tonal effect due to the roll-off rate saturates at around 100 dB per octave for the widest peak bandwidths tested, however, as the bandwidth becomes narrower, this saturation takes longer to occur, to the point that no saturation was observed for peak bandwidths that were 1% of the critical bandwidth. The saturation for large bandwidths is similar to that described by Fastl for low-pass filtered noise, however, this saturation occurs at a higher roll-off rate for band-pass filtered noise. Presumably, as the band-pass filter's lower cut-off frequency approaches 0 Hz, the saturation will approach a roll-off rate of 36 dB per octave. The use of trapezoidal filters is a practical choice for the evaluation of the tonalness of band-passed noise. Although tonal components in sounds will, in general, not have trapezoidal spectral shapes, the general conclusions should still be valid.

A consequence of the interaction between roll-off rate and peak bandwidth is that it is not sufficient to only consider peak bandwidth of a band-pass filtered noise when estimating how tonal it will sound. In Aures's tonalness metric, a bandwidth estimate is required for the determination of w_1, however, Aures's model did not include roll-off rate effects. Aures's metric could be improved if a suitable bandwidth can be calculated, that is a function of both peak (or K dB down) bandwidth and roll-off rate, and used in the w_1 calculation. Or, does the w_1 function need to be changed? This is the subject of on-going research.

7. References

[1] Aures, W., "Procedure for Calculating the Sensory Euphony of Arbitrary Sound Signals", Acustica, 59:130–141, 1985.

[2] Daniel, P., Ellermeier, W., and Vormann, M., "Computational and Subjective Procedures for the Assesment of Sounds with Weak Tonal Components".

[3] Vormann, M., Verhey, J. L., Mellert,V., and Schick, A., "Subjective Rating of Tonal Components in Noise with an Adaptive Procedure", http://www.physik.uni-oldenburg.de/Docs/aku/staff/matthiasv.htm, 2000.

[4] Wiesmann, N., and Fastl, H., "Ausgepraegtheit der Tonhoehe und Frequenzunterschiedsschwellen von Bandpass-Rauschen", Fortschritte der Akustik, DAGA '91:505-508, 1991.

[5] Wells, R. J., "Calculation of Annoyance Level for Sounds Containing Multiple Pure Tones", 78^{th} Meeting of the Acoustical Society of America, 1969.

[6] American Federal Aviation Agency (FAA), "Federal Aviation Regulations, Part 36 Appendix A", 1978.

[7] Zwicker, E., "On the dependence of unbiased annoyance on loudness," Proc. Internoise 89, pp. 809–814

[8] Zwicker, E. and Fastl, H., "Psychoacoustics, Facts and Models", Springer, 1999.

[9] Hastings, A. and Davies, P., "An Examination of Aures's Model of Tonality", Inter · Noise 2002, 2002.

[10] Vormann, M., Meis, M., Mellert, V., and Schick, A., "A New Approach for the Evaluation of Tonal Noise (Tonality)", http://www.physik.uni-oldenburg.de/Docs/aku/staff/matthiasv.htm, 1999.

[11] Moore, B. C. J., "An Introduction to the Psychology of Hearing", Academic Press, 1997.

[12] Rabine, L. R. and Gold, B., "Theory and Application of Digital Signal Processing", Prentice - Hall, 1975.

[13] Bradley, R. A., "Paired Comparisons: Some Basic Procedures and Examples", Handbook of Statistics Vol. 4, Elsevier Science Publishers, 1984.

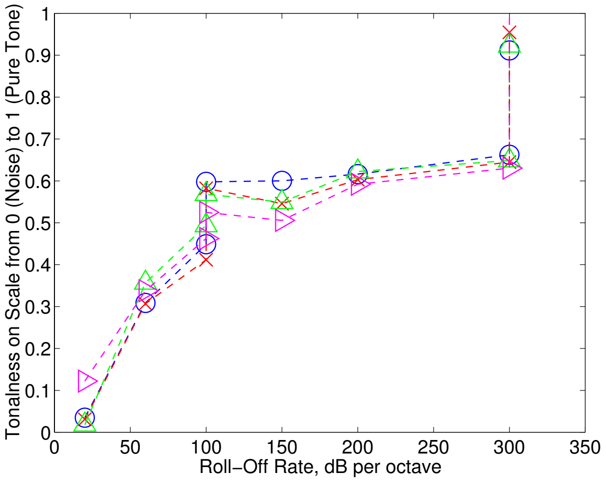

Figure 8: *Rescaled tonality for sounds common to all three experiments.* ○ *- rescaled direct scaling experiment result.* × *- rescaled paired comparison experiment result.* ▷ *- rescaled Aures tonality for the reference sounds deemed to have the same average tonalness as the test sounds.* △ *- rescaled average signal-to-noise ratio for the reference sounds deemed to have the same average tonalness as the test sounds.*