

On the Pitch Strength of Bandpass Noise in Normal-Hearing and Hearing-Impaired Listeners

Trends in Hearing
Volume 22: 1–14
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DOI: 10.1177/2331216518787067
journals.sagepub.com/home/tia



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Abstract

The psychoacoustic measure *pitch strength* describes the strength of the tonal sensation evoked by a sound on a scale from weak to strong. For normal-hearing listeners, it was shown in the literature that pitch strength of bandpass noise (relative to the pitch strength of a sinusoid at its center frequency) decreases with increasing bandwidth. This decrease also depends on the center frequency. These effects were often attributed to the frequency selectivity of the auditory system. The present study investigated the relative pitch strength of bandpass noise in hearing-impaired listeners and for comparison in a normal-hearing control group. For the normal-hearing listeners, pitch strength was measured at sound pressure levels of 30 and 70 dB SPL for bandwidths between 5 and 1620 Hz and center frequencies of 375, 750, and 1500 Hz. In addition, two ways of generating the stimuli (filtering in frequency or time domain) were used to compare the data with previous results. Apart from the known effect of center frequency on the change of relative pitch strength with increasing bandwidth, stimulus generation also had a significant influence on the results. Relative pitch strength of bandpass noise in hearing-impaired listeners was measured for bandwidths from 5 to 1620 Hz; the center frequency was 1500 Hz. Compared with the corresponding results of the normal hearing, relative pitch strength was altered in the hearing-impaired listeners. These alterations, however, could not be explained by altered spectral processing in the damaged cochlea alone.

Keywords

psychoacoustics, pitch perception, hearing disorders

Date received: 15 November 2017; revised: 31 May 2018; accepted: 1 June 2018

Introduction

The perceptual measure of pitch is an important aspect in the field of speech and music. Tonal components are common in environmental sounds and can help the listener to identify their sources. Regarding environmental noise, they can also be especially annoying (Hansen, Verhey, & Weber, 2011). Standards like the ANSI S1.13 (2005), the DIN 45681 (2005), the IEC 61400-11 (2006), and the ISO 1996-2 (2007) consider the altered perception of noises containing tonal components. The German standard DIN 45681 (2005) determines tone adjustments for environmental noises that contain tonal components and thereby limits noise immissions for this kind of noises. To decide on the height of the necessary tone adjustment, the difference in sound pressure levels of the tonal component and the portion of the background noise around the tonal component are computed. However, this does not only refer to pure tones, as

narrowband noises are known to elicit tonal sensations and therefore can be tonal components as well. This was accounted for by the German standard by allowing a tonal component to have a certain bandwidth. The magnitude of the tonal character of a bandpass noise is described as its *pitch strength*.

The psychoacoustic measure of pitch strength describes the strength of the tonal sensation evoked by a certain sound on a scale from faint to strong (distinct). Being a relative measure, it can only be assessed using anchor sounds (Fastl & Zwicker, 2007, p. 135).

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Fastl and Stoll (1979) scaled the pitch strength of a number of different acoustical stimuli in relation to a pure tone and comb-filtered noise. They found that pure tones evoked the strongest pitches. For complex tones and noise bands, pitch strength was reduced. This led to the assumption that line spectra (and very narrow noise bands) evoke the strongest pitches, whereas continuous spectra show reduced pitch strengths. Fastl and Zwicker (2007, pp. 135–139) also showed dependencies of pitch strength of pure tones on duration, level, and frequency.

For bandpass noise, the pitch strength decreases with increasing bandwidth when the stimulus' center frequency is kept constant. When the bandwidth is fixed, pitch strength increases with increasing center frequency (Fastl & Zwicker, 2007, pp. 139–140). The critical band seems to play a role in these dependencies. It is assumed that the pitch strength of a certain sound decreases as soon as the sound's bandwidth exceeds the critical band (Fastl & Zwicker, 2007, p. 140). This could explain the correlation between the bandwidth of the noise and pitch strength: For small bandwidths, pitches are quite distinct and strong as the sound's bandwidth is narrower than the auditory filter. The pitch strength strongly decreases when the bandwidth exceeds the critical bandwidth. As the critical bandwidth increases with the corresponding center frequency (Zwicker, 1961; Zwicker & Terhardt, 1980), pitch strength decreases faster for lower center frequencies.

Fruhmann (2004) also assumed that the dependency of pitch strength on center frequency is due to the varying critical bandwidth at different center frequencies. Therefore, he measured pitch strength for stimuli with bandwidths relative to the critical bandwidth. However, the hypothesis that pitch strength only depends on the sound's bandwidth in relation to the critical bandwidth of the corresponding center frequency could neither be entirely proven nor rejected, as significance was missed.

It may well be that other parameters may also play a role in pitch strength. For example, temporal cues might contribute to the perception of pitch strength. Shofner and Selas (2002) measured pitch strength of various complex sounds. Results were evaluated using a modified form of Steven's power law, which considered both the envelope (E) and the temporal fine structure (TFS) of a sound. Their results suggested that TFS has the greatest impact on pitch strength and mainly determines it. E cues, however, may also play a role.

In listeners with sensorineural hearing loss, both pathologically widened auditory filters and deficits in the use of information from a sound's TFS lead to alteration in the acoustical perception. Glasberg and Moore (1986) measured auditory filter bandwidths in participants with unilateral hearing loss using the normal ear and the impaired ear for a direct comparison. For the normal ears, they found normal or nearly normal results

with an asymmetric shape and physiological bandwidths. In the impaired ear, however, they all showed broader auditory filters than for the normal ear. Lorenzi et al. (2006) did an experiment on the ability of normal-hearing and hearing-impaired listeners to use cues from the E or the TFS of a sound to understand speech. Normal-hearing participants scored perfectly assessing the unprocessed speech and nearly perfectly for E and TFS speech. Hearing-impaired listeners, however, although performing very well for unprocessed speech and E speech, had huge difficulties assessing TFS speech. This led to the assumption that hearing-impaired listeners have deficits in using TFS information. Hopkins and Moore (2007) used so-called shaped and nonshaped stimuli to test the listeners' ability of using TFS cues. Shaped stimuli were bandpass filtered and therefore contained no spectral cues, so that listeners could only assess the sound's TFS. Normal-hearing participants could complete the task reliably for both shaped and nonshaped stimuli. However, hearing-impaired participants could only distinguish between the nonshaped stimuli, while performing very poorly on the shaped stimuli. The authors attributed this finding to a missing ability to use TFS cues in hearing-impaired participants. Due to pathologically widened acoustical filters and deficits in the use of a sound's TFS information, an alteration in the perception of pitch strength in listeners with cochlear hearing loss seems possible.

First evidence for such an altered pitch strength was provided in Leek and Summers (2001) for iterated rippled noise. They found that hearing-impaired participants showed a reduced pitch strength compared with normal-hearing listeners as they assessed weaker pitch strengths for all tested stimuli. They also found that the most striking differences were in the regions of greatest hearing loss and considered the broader auditory filters in hearing-impaired listeners leading to a reduced spectral resolution as a possible reason.

This study explores pitch strength of bandpass noises relative to the pitch strength of a sinusoid at the center frequency of the noise in normal-hearing and hearing-impaired listeners. For normal-hearing listeners, the dependency of relative pitch strength on the combination of bandwidth, center frequency, sound pressure level, and different types of filtering was investigated. This allows for the comparison to the data shown in Fastl and Zwicker (2007, pp. 139–140). For listeners with sensorineural hearing loss, the dependency of pitch strength on the sound's bandwidth was investigated. Their results were compared with the results from the normal-hearing listeners at the same bandwidths, center frequency, and comparable loudness or approximately equal sound pressure level. This addressed the question of whether sensorineural hearing loss influenced their pitch-strength perception of bandpass noises significantly.

Experiment I: Pitch Strength in Normal-Hearing Participants

In this experiment, relative pitch strength in normal-hearing participants was measured for bandpass noises with various bandwidths, sound pressure levels, and center frequencies. Two different methods were used to generate the stimuli.

Method

Participants. Twenty-two normal-hearing participants (NH1–NH22; 7 female, 15 male) aged from 22 to 27 years (mean: 24 years) took part in Experiment 1. Their absolute hearing thresholds in quiet were determined prior to their participation. All participants showed thresholds in quiet ≤ 20 dB HL at the standard audiometric frequencies between 125 Hz and 8 kHz (≤ 15 dB HL between 125 and 4000 Hz) in the tested ear, which was chosen randomly. Four of the 22 participants had previous experiences with psychoacoustic measurements. All participants took part voluntarily in the experiment and were paid for their participation. Written informed consent was provided by all participants. Approval was given by the Ethics Committee of the Medical faculty of the Otto von Guericke University (Approval Number 10/13).

Stimuli and procedure. Relative pitch strength of Gaussian noise bands was measured in a magnitude estimation procedure. The noise bands had bandwidths of 5, 15, 45, 135, 405, 810, 1215, or 1620 Hz and were geometrically centered at 375, 750, or 1500 Hz. Two methods were used to generate these noise bands referred to as Filter A and Filter B in the following:

Filter A: A white noise was transferred into the frequency domain, and all Fourier components outside the desired frequency range were set to zero. An inverse Fourier transform back into the time domain led to the desired signal. This method of filtering was used, for example, in Hots, Jarzombek, and Verhey (2016) and Hots, Rennies, and Verhey (2014).

Filter B: Noise bands were generated using third-order Butterworth bandpass filters. This led to 18 dB per octave flanks on both sides of the spectrum and aimed at using the same method of filtering as in Fastl and Zwicker (2007). In the following, the bandwidths of the stimuli generated with this method of filtering refer to the 3 dB bandwidth.

Figure 1 compares spectra of stimuli generated in these two different ways. Each panel shows the magnitude spectra of stimuli at a center frequency of 1500 Hz

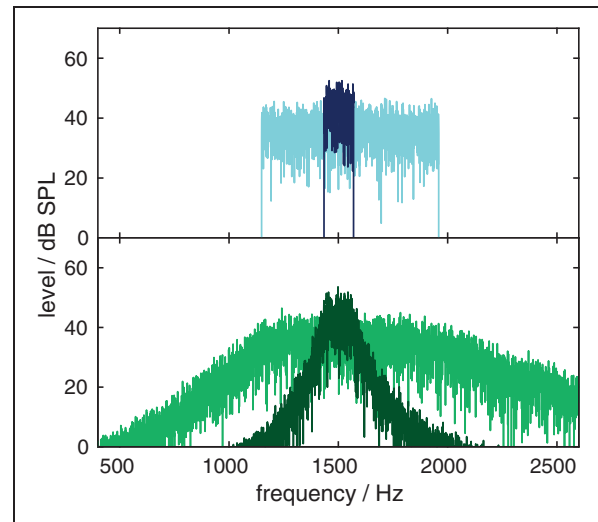


Figure 1. Magnitude spectra of the study's stimuli. The top panel (blue lines) shows the spectra of A-type stimuli with bandwidths of 135 Hz (dark blue) and 810 Hz (light blue) with 1500 Hz center frequency and 70 dB SPL. The bottom panel (green lines) shows the spectra of B-type stimuli with the same bandwidths of 135 Hz (dark green) and 810 Hz (light green) with 1500 Hz center frequency and 70 dB SPL.

for the bandwidths of 135 and 810 Hz. The upper panel shows the spectra of the stimuli generated using Filter A (A-type stimuli; blue). They are quite narrow with steep slopes at the cutoff frequencies. The bottom panel shows the spectra of the stimuli generated using Filter B (B-type stimuli; green). They are much broader than the corresponding A-type stimuli due to the shallower slopes of the filter.

All stimuli had a duration of 500 ms including 50-ms \cos^2 ramps at signal on- and offset and levels of 30 or 70 dB SPL. They were generated digitally at a sampling rate of 44.1 kHz using Matlab (Mathworks) and were presented monaurally via an external soundcard (RME Fireface 400) and headphones (Sennheiser HD 650).

The experiment was completed in two sessions which were held on two separate days. One session used stimuli generated with Filter A, the other session's stimuli were generated using Filter B. The normal-hearing participants were split into two groups which completed both sessions in an opposite order (NH1–NH11 started with Filter A, NH12–NH22 started with Filter B). Both sessions consisted of six runs, which were completed in a random order. In every run, the center frequency and the sound pressure level were kept constant, whereas the bandwidths were varied. Stimuli with the different bandwidths were randomly measured three times within one run leading to a total of 24 stimuli per run. Prior to the actual experiment, participants had the chance to become acquainted with the task of assessing pitch strength by completing a short test run at

a center frequency of 1000 Hz and a sound pressure level of 50 dB SPL. This test run contained four stimuli with bandwidths of 5, 135, 810, and 1620 Hz, which were presented twice in a random order.

To perform the experiment, two different user interfaces were generated in Matlab. With the help of the first interface, participants were asked to familiarize with the measure *pitch strength*. Three panels with three sounds differing in their pitch strengths were presented. One panel was marked *weak* (German: *gering*) playing a sound with a bandwidth of four times the center frequency; another panel labeled *more* (German: *mehr*) played a sound with a bandwidth of 0.2 times the center frequency; the third panel *clear* (German: *deutlich*) played a sound with a bandwidth of 0.04 times the center frequency. The sound pressure and the center frequency of these samples were the same as in the following experimental run. To reduce potential bias effects, the bandwidths and the categories were not used in the main experiment. The participants could listen to the samples as often as they liked. This first interface appeared before every single run. Participants were asked to listen to the samples every time before starting a new run. Via panel *start experiment* (German: *Experiment starten*), the participants started the actual experiment independently, and the second user interface appeared on the screen.

This interface is shown in Figure 2. After pressing the panel *Play* (German: *Abspielen*), the stimulus was presented. The panel labeled “100%” played a pure tone with the frequency and sound pressure level of the current run. This sound was used as a reference with a pitch strength of 100%. Due to this choice of reference, only the pitch strength relative to the tone at the center frequency of the noise and at the same level as the noise is measured. This is referred to as the relative pitch strength in the following. A slider was placed in the center of the interface. The slider’s starting position was set to the center of the bar. The participants’ task was to compare the pitch strength of the stimulus to the pure tone and visualize their estimation of the stimulus’ relative pitch strength by moving the slider to the corresponding position. A short explanation of this task was placed in the upper right corner of the interface. Below this, the individual number of the current stimulus out of the run’s 24 (8 in the test run) stimuli was shown.

The participants could listen to both the stimulus and the reference tone as often as they liked and change the slider’s position. However, the slider had to be moved for every stimulus to continue the experiment. By touching the panel *Next* (German: *Weiter*), the participants could move on to the next stimulus. After that, there was no possibility for the participants to return to the previous

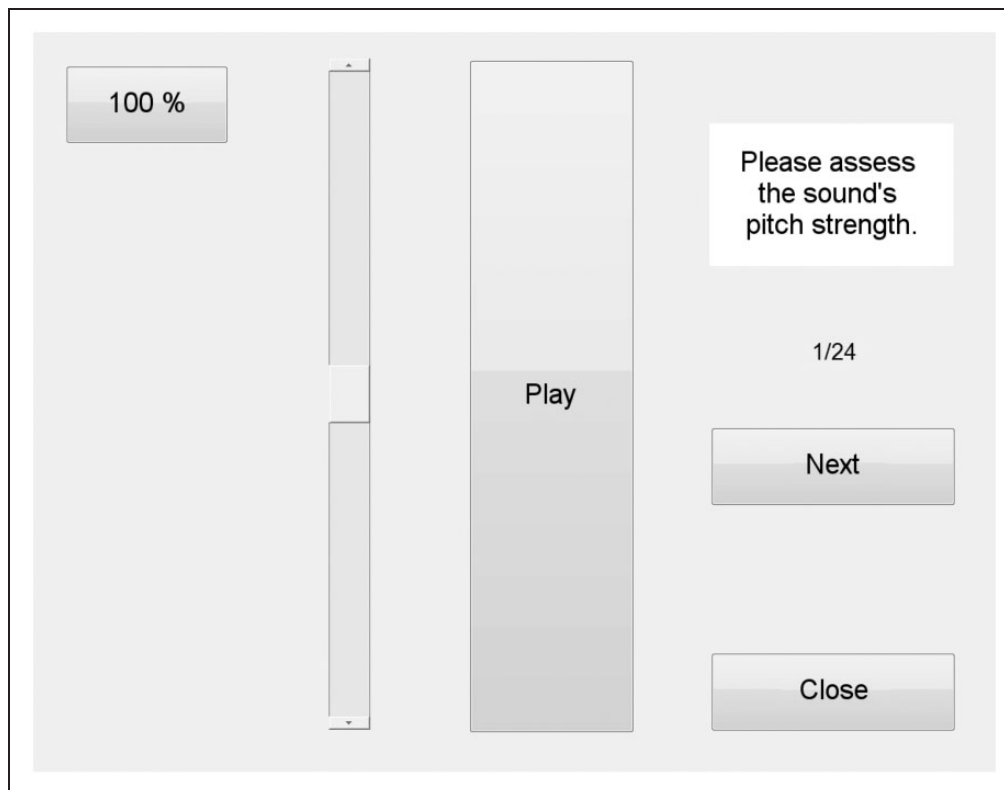


Figure 2. User interface used in the study. Relative pitch strength was measured in reference to a pure tone (100%).

stimuli. The slider returned to the center position again, and the next stimulus had to be assessed. The panel *Close* (German: *Beenden*) canceled the current run without saving any data. After having estimated the pitch strength of a run's 24th stimulus, the user interface was closed by the trial manager and the next run was started, beginning with the samples. If necessary, the participants were given the opportunity to take a short break in between two runs. Before the experiment, a short standardized oral explanation of the psychoacoustic measure *pitch strength* was given, and detailed written information on the experiment and the user interfaces were offered to the participants. During the experiments, all participants were seated in a double-walled soundproof booth facing a touch screen that was used for the experiment. In case of occurring questions, participants always had the possibility to get in contact with the examiner via a window in the booth.

Results

Figures 3 and 4 display the results for the normal-hearing listeners at 30 and 70 dB SPL, respectively. The medians across all participants and interquartile ranges are shown. In the individual results (not shown), the participants show some variations in the results of the three repetitions of each condition. For most conditions, the intraindividual standard deviations are rather small; however, for single conditions and participants, they reach higher values. In total, they range from 0% to about 43% with a mean across all conditions and all participants of about 6.5%. The relative pitch strength of bandpass noise is shown as a function of bandwidth using medians and interquartile ranges. Each curve indicates data of one center frequency. The top panel and the blue symbols and lines in both figures show the data for Filter A, the bottom panel and the green symbols and lines in both figures show the data for Filter B.

For both stimulus types and sound pressure levels, relative pitch strength decreases with increasing bandwidth, and this decrease depends on the center frequency. For medium bandwidths (45 Hz, 135 Hz, and 405 Hz), relative pitch strength increases with increasing center frequency. For the center frequencies considered here, it is likely that this effect would have been larger if pitch strength had been measured relative to 1.5 kHz for all bandwidth-center-frequency combinations considered here, since relative pitch strength tends to be smaller for 375 Hz than for 1500 and 3000 Hz (Fastl & Zwicker, 2007, p. 139).

The gray symbols and lines in Figures 3 and 4 indicate the data from Fastl and Zwicker (2007, p. 139). Note that they show the relative pitch strengths of bandpass noises with center frequencies of 250 (filled diamonds), 500 (open circles), 1000 (filled circles), 2000

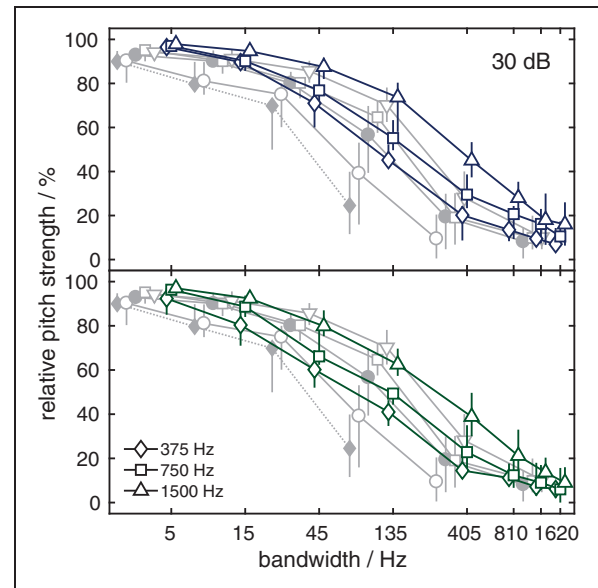


Figure 3. Results for normal-hearing listeners at 30 dB SPL. Pitch strength is displayed as a function of bandwidth for the center frequency of 375 Hz (diamonds), 750 Hz (squares), and 1500 Hz (triangles). The top panel shows the data for A-type stimuli (blue lines and symbols), and the bottom panel shows the data for B-type stimuli (green lines and symbols). All data are compared with the data from Fastl and Zwicker (2007, p. 139; gray lines and symbols). Note that their data differed from the present study in center frequency (250 Hz, filled diamonds; 500 Hz, open circles; 1000 Hz, filled circles; 2000 Hz, open squares; 4000 Hz, open triangles), bandwidth (3.16, 10, 31.6, 100, 316, and 1000 Hz), and sound pressure level (50 dB SPL). Error bars display medians and interquartile ranges.

(open squares), and 4000 Hz (open triangles), that is, not the same center frequencies as in the present study. The choice of bandwidths and level also differed from the present study. They used a level of 50 dB SPL and bandwidths of 3.16, 10, 31.6, 100, 316, and 1000 Hz. This choice of bandwidths apparently was motivated by the use of a Brüel & Kjær 1027 signal generator. For both sound pressure levels tested in this study, A-type stimuli show more deviation from Fastl and Zwicker's data than B-type stimuli. Especially concerning medium bandwidths (135, 405, and 810 Hz), relative pitch strength of A-type stimuli decreases with bandwidth not as fast as in the data from Fastl and Zwicker. Data for B-type stimuli show less deviation from their data. Up to a bandwidth of 45 Hz and for the largest two bandwidths, the data from the literature and the present data at both sound pressure levels are very similar. At 405 and 810 Hz, the present data are slightly higher than in the literature.

When comparing data for the two stimulus types at 30 dB SPL (Figure 3), differences are greatest for the center frequency of 1500 Hz: At a bandwidth of 45 Hz, the difference is about 10%, at the 135 Hz bandwidth, there is a difference of about 15%, and at 810 Hz,

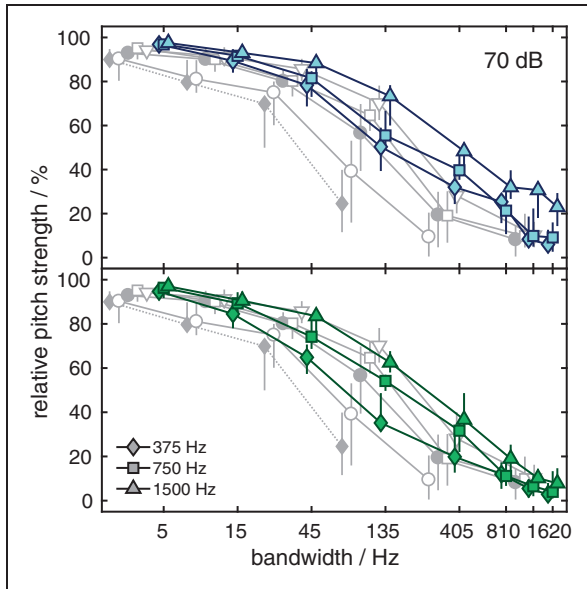


Figure 4. Results for normal-hearing listeners at 70 dB SPL. In contrast to Figure 3, own data are shown with filled symbols. Otherwise, data representation is the same as in the previous figure.

it amounts to 5%. At the largest bandwidths, data for A-type stimuli do not reach a relative pitch strength as weak as that for the B-type stimuli. For center frequencies of 375 and 750 Hz, data of the two stimulus types hardly show any differences.

When comparing data for the two stimulus types at 70 dB SPL (Figure 4), there are great differences for the center frequencies of 375 Hz and 1500 Hz: At a bandwidth of 45 Hz, the difference is about 15% for the center frequency of 375 Hz, for bandwidths of 135 Hz and 405 Hz, there is a difference of about 10% for both center frequencies, and at 810 Hz, it amounts to 10% for the center frequency of 375 Hz and 15% for the center frequency of 1500 Hz. Even at bandwidths of 1215 Hz and 1620 Hz, A-type stimuli are about 15% and 10% stronger in pitch for the center frequency of 1500 Hz, whereas for the center frequencies of 375 and 750 Hz, data of the two stimulus types hardly show any differences for the broadest noises.

For each condition, the mean relative pitch strength was calculated from the three data sets for each participant. The statistical data analysis was performed in SPSS using a factorial repeated-measures analysis of variance. The analysis revealed significant effects of all parameters—bandwidth, center frequency, sound pressure level, and type of filtering—on the relative pitch strength of bandpass noise in normal-hearing listeners.

As Mauchly's test indicated the assumption of sphericity had been violated for the effects of bandwidth, $\chi^2(27) = 146.37$, $p < .001$, the degrees of freedom were corrected using Greenhouse-Geisser estimates of

sphericity ($\epsilon = 0.29$). There was a highly significant effect of bandwidth on the relative pitch strength of bandpass noise, $F(2.01, 42.11) = 1105.60$, $p < .001$. Post hoc tests using a Bonferroni correction for multiple comparisons revealed that for every bandwidth, relative pitch strength differed significantly from those for all other bandwidths ($p < .001$).

The center frequency had a significant effect on the relative pitch strength of bandpass noise, $F(2, 42) = 268.73$, $p < .001$. Post hoc tests using a Bonferroni correction for multiple comparisons revealed that for every center frequency, relative pitch strength differed significantly from those for all other center frequencies ($p < .001$).

Sound pressure level had a significant effect on the relative pitch strength of bandpass noise, $F(1, 21) = 4.76$, $p = .04$, as did the type of filtering, $F(1, 21) = 47.09$, $p < .001$.

Experiment 2: Pitch Strength in Participants With Sensorineural Hearing Loss

In this experiment, relative pitch strength in participants with sensorineural hearing loss was measured for bandpass noises with various bandwidths and compared with results from the normal-hearing participants at a comparable loudness and approximately equal sound pressure level.

Method

Participants. Fifteen participants with cochlear hearing loss (HI1–HI15) took part in this experiment. They were aged from 24 to 74 years (mean: 63 years). One participant (HI15) was later excluded from the study as he admitted serious problems in understanding the task just after having completed the experiment. Before the experiment, hearing thresholds in quiet were determined for the participants to reflect the extent of their current hearing deficits. Participants were only included if they had thresholds between 30 and 60 dB for frequencies between 1000 and 2000 Hz and a flat hearing loss with no differences greater than 10 dB in this frequency region. The mean threshold at 1500 Hz was 51.4 dB HL. Subjects with a tinnitus or conductive hearing loss were excluded from the study too. The ear that matched the required criteria best was chosen. Table 1 provides the age, gender, and the audiogram of the ear used in this study for the hearing-impaired participants. Eleven out of these participants (HI1–HI8, HI10, HI14, and HI15) also took part in the study of Hots et al. (2016) and thus had previous experiences with psychoacoustic measurements. All participants took part voluntarily in the experiment and were paid for their participation.

Table 1. Age, Gender, and Audiogram of the Ear Used in the Experiment of the Hearing-Impaired Participants.

Participant	Age	Gender	Side	Audiogram										
				125	250	500	750	1000	1500	2000	3000	4000	6000	8000
HI1	68	M	L	40	45	55	60	60	60	55	65	65	90	105
HI2	78	F	L	25	25	40	45	50	45	50	55	65	60	60
HI3	69	F	R	15	20	35	40	50	50	40	45	35	40	40
HI4	57	M	R	40	45	40	40	40	50	50	50	65	75	90
HI5	62	F	L	25	35	35	45	40	50	45	55	55	65	75
HI6	72	F	R	40	45	60	60	60	55	50	60	70	70	80
HI7	52	M	L	45	50	55	55	55	50	40	35	45	50	60
HI8	68	M	R	15	20	30	40	40	55	55	60	70	90	80
HI9	54	F	L	45	50	55	60	55	55	60	55	50	75	80
HI10	24	F	R	25	25	25	25	30	30	40	40	45	50	50
HI11	74	F	R	45	45	50	55	60	55	55	55	55	55	80
HI12	71	F	L	30	40	45	45	40	45	50	45	50	75	70
HI13	62	F	R	25	30	35	40	40	45	40	50	55	60	60
HI14	74	M	R	50	45	40	45	50	60	55	65	75	100	100

Note. M = male; F = female; L = left; R = right.

Thresholds in quiet are given in dB HL for the audiometric frequencies in Hz.

Written informed consent was provided by all participants. Approval was given by the Ethics Committee of the Medical faculty of the Otto von Guericke University (Approval Number 10/13).

Stimuli and procedure. The setup, the user interfaces, and their handling were identical to the procedure used for normal-hearing participants. The noise bands in this experiment were generated using Filter A (see Experiment 1). The same bandwidths (5, 15, 45, 135, 405, 810, 1215, and 1620 Hz) were used, and the noise bands were geometrically centered at 1500 Hz. The sound pressure level was set to an individual level, which evoked approximately the same loudness in the participant as a sound of 30 dB SPL in a normal-hearing listener. Again, every condition was measured three times. This resulted in a total of 24 randomly presented stimuli. The individual sound pressure level L was calculated using the following equation, which is taken from Hots et al. (2016) who measured loudness of subcritical noise bands in hearing-impaired participants.

$$L = thr_{HI} + \frac{ucl_{HI} - thr_{HI}}{ucl_{NH} - thr_{NH}} \times 30 \text{ dB SPL}$$

with thr being the threshold in quiet at 1500 Hz and ucl the uncomfortable loudness. The suffix NH indicates average normal-hearing values, where the suffix HI indicates individual values for a hearing-impaired listener.

Eleven participants in this study had participated in their study as well. If their current hearing threshold at

1500 Hz only differed from their threshold then by 5 dB or less, the same individual sound pressure level as in the loudness study of Hots et al. (2016) was used. This applied for 9 of the 11 participants. For all other participants, the individual threshold in quiet at 1500 Hz (thr_{HI}) was taken from the current audiogram, the uncomfortable level for normal-hearing and hearing-impaired listeners were set to $ucl_{NH} = 100$ dB HL and $ucl_{HI} = 100$ dB HL, and the normal-hearing threshold at 1500 Hz was set to $thr_{NH} = 0$ dB HL.

To test the individual level before the experiment, a 135-Hz wide noise and a pure tone were presented with the individual sound pressure level under study conditions. Five of the participants perceived the applied individual level as too soft to complete the task reliably. For them, a gain in level of 6 dB was applied. The mean individual sound pressure level was 66.6 dB SPL.

As for the normal-hearing participants, a previous test run was performed for stimuli with 1500 Hz center frequency and individual sound pressure levels for the stimuli with 5, 135, 810, and 1620 Hz bandwidth, which were presented twice in a random order.

Results

Figure 5 displays the individual results for hearing-impaired listeners HI1 to HI14. Every panel shows the relative pitch strength of bandpass noise as a function of bandwidth. Each data point pictures the individual mean calculated from the three repetitions for each condition. Error bars stand for the listener's individual standard deviation. The individual sound pressure level used in

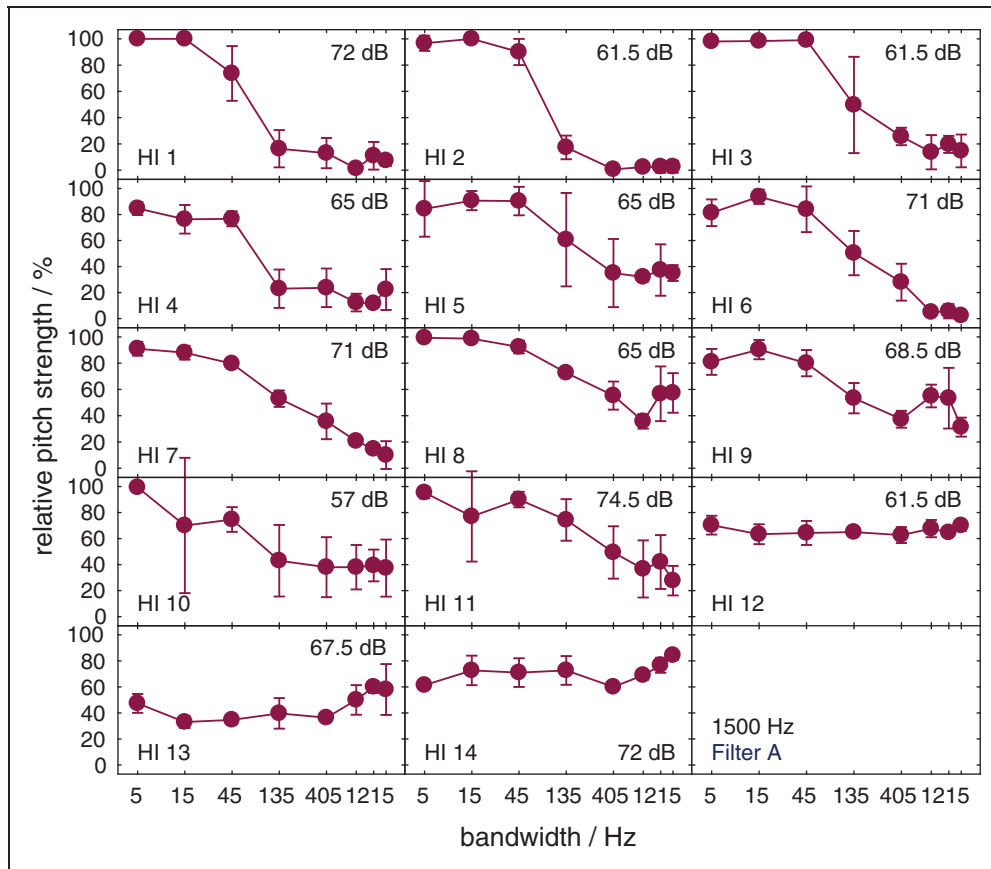


Figure 5. Individual results of the hearing-impaired listeners HI1 to HI14. Relative pitch strength is shown as a function of bandwidth for the center frequency of 1500 Hz and the individual sound pressure level. Data points stand for the listener's mean calculated from the three data sets. Error bars indicate standard deviations for each listener. The individual sound pressure level is noted in the top right corner (bottom right corner for HI14) of each panel.

the experiment is noted in the top right corner (bottom right corner for HI14) of each panel.

HI1 and HI2 used the whole dynamic range from 100 to 0%. They showed a very steep decrease in the relative pitch strength between the bandwidths of 45 Hz and 135 Hz until it reached 0% or 10%, respectively, for the four widest bandwidths. The data of HI3 were very similar to HI1 and HI2 but showed a little shallower decrease in relative pitch strength and did not reach values below 15%. HI4 showed a similar trend with a very steep decrease between the bandwidths of 45 Hz and 135 Hz. However, this participant rated the relative pitch strengths for the smallest bandwidths weaker than the other participants (80%–85%). HI5 to HI7 showed a more continuous and shallower decrease with increasing bandwidth. HI5 also showed a reduced dynamic range with a relative pitch strength of about 40% for the broadest bandwidths. HI8 to HI11 showed an even shallower decrease with reduced dynamic ranges of 60 to 70 percentage points and still quite strong relative pitch strengths for the broadest bandwidths. HI12 to HI14 showed no dynamic at all. They perceived all stimuli

approximately equally strong and ranged between 60% and 80% (HI12 and HI14) and 40% and 60% (HI13). Interestingly their standard deviations were also very small. A correlation analysis revealed that there is no correlation between the age or the amount of hearing loss and the dynamic range of the measured relative pitch strength in the hearing-impaired listeners.

Figure 6 compares the data of the hearing-impaired listeners (red circles and lines) to the data of the normal-hearing listeners at 30 dB SPL (open triangles and blue lines) and 70 dB SPL (blue triangles and lines) at a center frequency of 1500 Hz using Filter A. The relative pitch strength of bandpass noise is shown as a function of bandwidth. Medians and interquartile ranges are displayed. The range varies between listeners, with some showing a large range and some a very small range. In general, hearing-impaired listeners seem to have a reduced dynamic range in the perception of relative pitch strength. They perceive the relative pitch strength for a bandwidth of 5 Hz at about 90%; it hardly changes for 15 Hz and slightly decreases for 45 Hz (85%). For a bandwidth of 135 Hz, it steeply decreases to 50% and

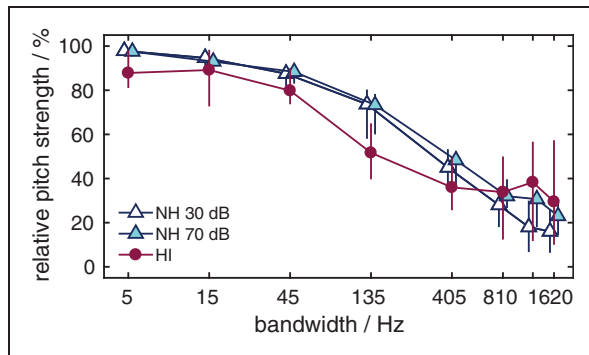


Figure 6. Comparison of the data for normal-hearing listeners (blue lines and triangles) and hearing-impaired listeners (red lines and circles). Relative pitch strength is shown as a function of bandwidth at a center frequency of 1500 Hz. Stimuli were generated using Filter A. Light blue filled triangles show the normal-hearing listeners' data for 70 dB SPL, unfilled triangles show the normal-hearing listeners' data for 30 dB SPL, and red circles show the hearing-impaired listeners' data for the individual sound pressure level (mean: 66.6 dB SPL). Medians and interquartile ranges are displayed.

reaches a constant relative pitch strength of about 30% for broader bandwidths. For the bandpass noises, this leads to a dynamic range of only about 60% between the relative pitch strengths of very narrow and very broad noises for the hearing-impaired participants. In comparison to this, normal-hearing listeners showed a dynamic range of about 80% for both sound pressure levels. Also, they show a steadier decrease from the bandwidth of 5 Hz (100%) to 15 Hz (95%), 45 Hz (90%), 135 Hz (75%), and 405 Hz (50%). At a bandwidth of 810 Hz, relative pitch strength reaches an approximately constant value of about 20 to 25% for all broader noises. Consequently, hearing-impaired listeners seem to perceive weaker relative pitches for bandwidths of up to 810 Hz, showing the greatest differences from normal-hearing listeners of about 25% at 135 Hz bandwidth. However, they seem to perceive very broad noises as having a larger relative pitch strength than the normal-hearing listeners.

For each condition, the mean relative pitch strength was calculated from the three data sets for each participant. The statistical data analysis was performed in SPSS using a factorial repeated-measures analysis of variance. As Mauchly's test indicated the assumption of sphericity had been violated for the effects of bandwidth, $\chi^2(27) = 128.72$, $p < .001$, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.20$). There was a highly significant effect of bandwidth on the relative pitch strength of bandpass noise in hearing-impaired listeners, $F(1.38, 17.94) = 23.86$, $p < .001$. Post hoc tests using a Bonferroni correction for multiple comparisons revealed the following significant differences: The pitch strength for the bandwidth

of 5 Hz differed significantly from those for 135 Hz ($p = .009$), 405 Hz ($p < .001$), 810 Hz ($p = .002$), 1215 Hz ($p = .005$), and 1620 Hz ($p = .005$). The pitch strength for the bandwidth of 15 Hz differed significantly from those for 135 Hz ($p = .024$), 405 Hz ($p = .002$), 810 Hz ($p = .006$), 1215 Hz ($p = .014$), and 1620 Hz ($p = .013$). The pitch strength for the bandwidth of 45 Hz differed significantly from those for 135 Hz ($p = .011$), 405 Hz ($p = .001$), 810 Hz ($p = .004$), 1215 Hz ($p = .011$), and 1620 Hz ($p = .011$). The pitch strength for the bandwidth of 135 Hz differed significantly from those for 5 Hz, 15 Hz, 45 Hz, and 405 Hz ($p = .003$). There was no significant difference in the pitch strengths for the bandwidths of 405 Hz, 810 Hz, 1215 Hz, and 1620 Hz.

To investigate the differences in relative pitch strength between the normal-hearing and hearing-impaired listeners, independent t tests were performed for each bandwidth. The tests were carried out for relative pitch strengths at comparable loudness and approximately equal sound pressure level. To eliminate the influence of multiple comparison, p^* values (which equal the p value multiplied with the Factor 8) were introduced. They were applied, wherever the t tests showed significant differences to create a second and stricter criterion of significance. If Levene's test indicated that the assumption of equal variances was violated, corrected values are reported. For relative pitch strength at comparable loudness (30 dB SPL for the normal-hearing and individual sound pressure level for the hearing-impaired listeners), the statistical analysis revealed the following significant differences ($M =$ mean, $SD =$ standard deviation): For the bandwidth of 5 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 97.74$, $SD = 1.55$) and hearing-impaired listeners ($M = 85.00$, $SD = 15.95$) differed significantly, $t(13.16) = 2.98$, $p = .01$. However, the stricter criterion for significance was missed ($p^* = 0.08$). For the bandwidth of 15 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 93.85$, $SD = 4.36$) and hearing-impaired listeners ($M = 82.29$, $SD = 18.70$) differed significantly, $t(13.91) = 2.26$, $p = .04$; the stricter criterion for significance was not met ($p^* = .32$). For the bandwidth of 135 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 71.20$, $SD = 12.69$) and hearing-impaired listeners ($M = 49.36$, $SD = 19.73$) differed significantly, $t(34) = 4.06$, $p < .001$. Even the stricter criterion for significance was met ($p^* < .008$). For the bandwidth of 1215 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 18.68$, $SD = 11.32$) and hearing-impaired listeners ($M = 35.38$, $SD = 24.48$) differed significantly, $t(16.59) = -2.39$, $p = .03$; the stricter criterion for significance was not met ($p^* = .24$). For the bandwidth of 1620 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 16.42$, $SD = 10.87$) and hearing-impaired listeners ($M = 32.88$, $SD = 25.98$) differed

significantly, $t(15.93) = -2.25$, $p = .04$; the stricter criterion for significance was not met ($p^* = .32$). For the bandwidths of 45 Hz, 405 Hz, and 810 Hz, relative pitch strengths in normal-hearing listeners did not differ significantly from those in hearing-impaired listeners.

For relative pitch strength at approximately equal sound pressure level (70 dB SPL for the normal-hearing and individual sound pressure level for the hearing-impaired listeners), the data analysis revealed the following significant differences: For the bandwidth of 5 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 96.92$, $SD = 2.57$) and hearing-impaired listeners ($M = 85.00$, $SD = 15.95$) differed significantly, $t(13.43) = 2.77$, $p = .02$; the stricter criterion for significance was not met ($p^* = .16$). For the bandwidth of 15 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 93.50$, $SD = 3.73$) and hearing-impaired listeners ($M = 82.29$, $SD = 18.70$) differed significantly, $t(13.66) = 2.21$, $p = .04$; the stricter criterion for significance was not met ($p^* = .32$). For the bandwidth of 135 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 70.83$, $SD = 10.46$) and hearing-impaired listeners ($M = 49.36$, $SD = 19.73$) differed significantly, $t(17.72) = 3.75$, $p = .001$; even the stricter criterion for significance was met ($p^* = .01$). For the bandwidth of 405 Hz, relative pitch strengths of bandpass noise for normal-hearing ($M = 46.42$, $SD = 9.15$) and hearing-impaired listeners ($M = 35.76$, $SD = 17.42$) differed significantly, $t(34) = 2.41$, $p = .02$; the stricter criterion for significance was not met ($p^* = .16$). For the bandwidths of 45 Hz, 810 Hz, 1215 Hz, and 1620 Hz, relative pitch strengths in normal-hearing listeners did not differ significantly from those in hearing-impaired listeners.

Discussion

The normal-hearing data show that the center frequency strongly influenced results with respect to the change in relative pitch strength with bandwidth in Hz. This might be connected to the relation of the sound's bandwidth to the critical band at a specific center frequency leading to a decrease in pitch strength once the critical band is exceeded (Fastl & Zwicker, 2007, pp. 139–140). As the critical bandwidth increases with its center frequency (Zwicker, 1961; Zwicker & Terhardt, 1980), pitch strength decreases at wider bandwidths for higher center frequencies. To test this hypothesis, a subset of the data for the normal-hearing listeners shown in Figures 3 and 4 is replotted in Figure 7 with the bandwidths expressed in Bark instead of Hz. The top panel shows the data for one filter type (A-type stimuli) at the two levels. The bottom panel shows the data at one level (70 dB SPL) for the two filter types. The symbols are the same as used in Figures 3 and 4. On the Bark scale, the

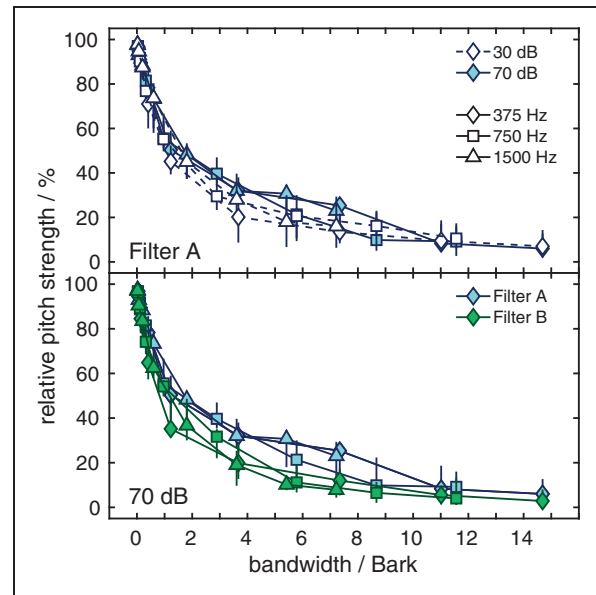


Figure 7. Mean pitch strength for normal-hearing listeners as a function of bandwidth in Bark. Otherwise, data representation is the same as in Figures 3 and 4. The top panel shows results for A-type stimuli at 30 dB SPL (open symbols) and 70 dB SPL (filled symbols). The bottom panel shows the data for A-type (blue lines and symbols) and B-type stimuli (green lines and symbols) at 70 dB SPL. In both panels, different symbols represent the different center frequencies of 375 Hz (diamonds), 750 Hz (squares), and 1500 Hz (triangles).

data at the same level and for the same filter type are very similar for the three center frequencies, supporting the hypothesis that the critical bandwidth at the center frequency of the noise accounts for a large portion of the effect of center frequency on the results.

In the bottom panel of Figure 7, the relative pitch strengths of the B-type stimuli are usually lower than those for the corresponding A-type stimuli. This is supported by the statistical analysis where, for the normal-hearing listeners, a significant difference in the method of filtering was shown. Filter A led to stronger pitches than Filter B. The magnitude spectra of both types of stimuli (shown for 135 Hz and 810 Hz bandwidths at a center frequency of 1500 Hz in Figure 1) show what may account for these differences: Spectra of A-type stimuli are quite narrow with very steep slopes at the cutoff frequencies. Spectra of B-type stimuli are broader with shallower slopes on both sides. Considering the assumption that pitch strength decreases with increasing bandwidth of the stimulus, narrow spectra may lead to stronger pitches, as—compared with broader spectra—they cover a reduced frequency range and thus contain less frequencies. Another aspect that may account for the stronger pitches that are perceived when using Filter A is the phenomenon of edge pitches. Fastl and Zwicker (2007, pp. 125–128) showed that noises with

steep spectral slopes can produce pitch sensations that correspond to the cutoff frequency. For bandpass noises, this means that two pitches are evoked at the spectral edges. However, for narrow-band noise with closer spectral edges, the elicited pitches fuse to a single pitch sensation close to the center frequency. Regarding the pitch strength of noise, it was shown in Fastl and Zwicker (2007, pp. 142–144) that pitch strength increased with the steepness of the filter slopes. This is in line with the data in this study. The steep filter slopes of Filter A might elicit edge pitches at the cutoff frequencies. These pitches might lead to the perception of stronger pitch strengths and could account for the differences between Filter A and Filter B stimuli. Also, the data showed no differences between both methods of filtering for small bandwidths. This agrees well with the observation that edge pitches do not occur for narrow-band noises. The consequence that needs to be drawn from this finding is that the type of filtering influences pitch strength in a way that needs to be paid attention to when planning measurements or comparing data from different studies on pitch strength.

Figures 3 and 4 compare the data on the relative pitch strength of bandpass noise in normal-hearing listeners from this study to the data from Fastl and Zwicker (2007, p. 139). Keeping in mind that different center frequencies were used in Fastl and Zwicker, this study could reproduce their data quite well with only slight deviations for medium bandwidths. As expected, relative pitch strength of bandpass noise in normal-hearing listeners depended on bandwidth and center frequency; significant effects of these two factors could be shown. As already mentioned in the Results section of Experiment 1, the present study (as well as Fastl & Zwicker, 2007) only measured relative pitch strengths, that is, due to the known effect of signal frequency of pitch strength of pure tones, the effect of these stimulus parameters on pitch strengths would have been presumably stronger for the parameters considered in the present study if it had been measured on an absolute scale, for example, on a categorical scale.

Fruhmann (2005, 2006b) developed an algorithm for the pitch strengths of various sounds. It used the Fourier-t-transform (Terhardt, 1985) to model the characteristics of the auditory system. This model could predict the pitch strength of various sounds quite well (Fastl, 2006; Fruhmann, 2006a). For bandpass noise, the model could predict the dependencies of pitch strength on bandwidth and center frequency correctly. However, predicted values did not always meet the interquartile ranges of the experimental data. This might indicate that this model of pitch strength for normal-hearing listeners does not cover all aspects of the data. Shofner and Selas (2002) assumed that TFS cues contribute to the perception of pitch strength as well. The model of

Fruhmann does not consider TFS in the sense of Shofner and Selas.

This study's data showed a significant effect of sound pressure level on how the perception of relative pitch strength in normal-hearing listeners changes with bandwidth of the noise: Relative pitch strength tends to decrease faster as bandwidth increases for 30 dB SPL than for 70 dB SPL. As in Fastl and Zwicker (2007, pp. 135–140) and Fastl and Stoll (1979), relative pitch strength was measured at equal sound pressure level. However, it should be considered that an increase in bandwidth might account for increasing loudness leading to varying loudness across the stimuli (Zwicker, Flottorp, & Stevens, 1957). To avoid this effect of loudness summation for broad noises, Fruhmann (2004) measured the relative pitch strength of bandpass noise in normal-hearing listeners at equal loudness. However, this did not show great deviations from the known data on the pitch strength in bandpass noise at equal level.

The data also indicate that the perception of relative pitch strength of bandpass noise in hearing-impaired listeners differs from normal-hearing listeners (see Figure 6). For the smallest bandwidths (5 Hz, 15 Hz, and 45 Hz) hearing-impaired listeners tended to perceive weaker pitches relative to the pitch strength of the tone than normal-hearing listeners, although no significant difference could be found. For the bandwidth of 135 Hz, however, significance could be shown. Figure 6 indicates that hearing-impaired listeners perceived a weaker relative pitch strength for this bandwidth. These findings go well with data on the pitch strength of iterated rippled noise in hearing-impaired listeners (Leek & Summers, 2001). Hearing-impaired listeners showed weaker pitch strengths for all tested stimuli. Reduced spectral resolution was considered as one possible explanation.

It is known that hearing-impaired listeners show pathologically widened auditory filters (Glasberg & Moore, 1986; Leek & Summers, 1993; Moore, Peters, & Glasberg, 1990; Patterson & Nimmo-Smith, 1980; Tyler et al., 1984). Consequently, their critical band is exceeded at larger bandwidths, that is, wider bandpass noises, than the critical band in normal-hearing listeners. Considering the assumption that the relative pitch strength of bandpass noise decreases as soon as the noise's bandwidth exceeds the critical band (Fastl & Zwicker, 2007, pp. 139–140), this would lead to a smaller decrease in relative pitch strength with bandwidth increases for hearing-impaired listeners than for normal-hearing listeners. This broadening of the auditory filters is likely to be a consequence of a damage to the active processes in the cochlea. To test the effect of a loss of active processes in the cochlea, the data were simulated with the dual resonance nonlinear filterbank model with the parameter set proposed by Lopez-Poveda

and Meddis (2001). Within this model framework, a cochlear damage of the active processes can be simulated by only considering the linear pathway of the dual resonance nonlinear filter. As a measure of the pitch strength, the ratio of the average intensity of the auditory filter at the signal frequency to the average intensity of the adjacent auditory filters was calculated. This approach was motivated by the prominence ratio proposed in the ANSI S1.13 to determine the tonal prominence. The standard tends to quantify a somewhat different sensation (tonality or magnitude of tonal content), but the measure may also serve as a first approximation of pitch strength since it is a measure of how peaky the excitation at the level of the cochlea is. The relative pitch strength for a bandpass noise was then determined by normalizing it to the intensity ratio of the tone at the center frequency of the noise and at the same level as the noise. Note the *ad hoc nature* of this approach, that is, none of the parameters were adjusted to better predict the experimental results. The bottom panel of Figure 8 shows predictions for the data shown

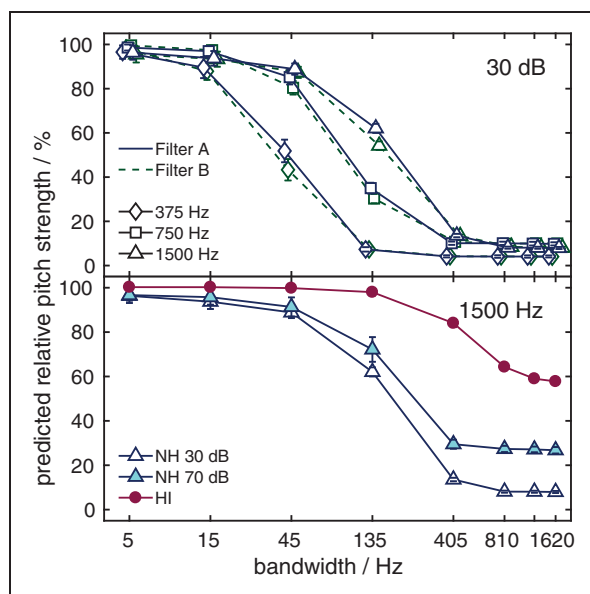


Figure 8. Predicted relative pitch strength as a function of bandwidth. Top panel: Predictions of the full (normal-hearing) model for A-type (blue lines and symbols) and B-type stimuli (green lines and symbols) with center frequencies of 375 Hz (diamonds), 750 Hz (squares), and 1500 Hz (triangles) at a level of 30 dB SPL. Bottom panel: Predictions for A-type stimuli at a center frequency of 1500 Hz of the full nonlinear (normal-hearing) model (blue lines and triangles) at levels of 30 dB SPL (open triangles) and 70 dB SPL (filled triangles) and for the linear (hearing-impaired) model at a level of 70 dB SPL (filled circles). Symbols and error bars represent the mean and standard deviation of 100 calculations.

in Figure 6. For the normal-hearing predictions, the full nonlinear model was used, whereas for the predictions of the hearing-impaired listeners, a linear version of the model (omitting the nonlinear pathway in all filters) was used. As expected, the change in predicted relative pitch strength as the bandwidth increases is more subtle with the linear model than with the nonlinear model. Note that the predictions of the nonlinear model differ between the two levels. This is due to the simulated change in auditory filter width with level.

The top panel shows the predicted results of the nonlinear model for the A-type stimuli (blue lines and symbols) and B-type stimuli (green lines and symbols) with center frequencies of 375 Hz (diamonds), 750 Hz (squares), and 1500 Hz (triangles) at a level of 30 dB SPL. For medium bandwidths, the model predicts lower relative pitch strengths for B-type stimuli than for A-type stimuli. This is also observed in the experimental data, as shown in the top panel of Figure 7, although the effect seems to be slightly stronger in the experimental results. This may be due to the simplified criterion used in the model. This does not consider, for example, possible effects of edge tones on the relative pitch strength.

Note that the hearing-impaired model predicts larger relative pitch strengths than the normal-hearing model. However, the experimental data show the opposite effect with weaker relative pitch strengths for hearing-impaired listeners. Thus, pathologically widened auditory filters are unlikely to account for these findings. A possible explanation can be given considering the use of TFS cues for the perception of pitch strength in normal-hearing listeners (Shofner & Selas, 2002). Hearing-impaired listeners were found to show a deficit use of TFS cues (Hopkins & Moore, 2007; Lorenzi et al., 2006; Moore, 2008; Moore, Glasberg, & Hopkins, 2006). This could lead to deficits in the perception of pitch strength and account for weaker relative pitch strengths at small bandwidths. However, it should be noted that in the present study, only relative pitch strengths were measured, that is, differences in the perception of absolute pitch strength between hearing-impaired listeners and normal-hearing listeners are not assessed. It could well be that absolute pitch strengths were weaker (or stronger) than for normal-hearing listeners for all stimuli used in the present study, that is, also for the reference sinusoid. The present data only allow for an analysis of differences in the effect of bandwidth on the relative pitch strength. An additional limitation is the large interindividual variability that was found in the hearing-impaired participants (see Figure 5).

As mentioned earlier, some of the hearing-impaired participants from this study also participated in a study which found that mid-bandwidth loudness depression, that is, a reduced loudness for bandpass noises with a

bandwidth close to the critical bandwidth can also be observed in hearing-impaired listeners (Hots et al., 2016). However, compared with normal-hearing listeners (Hots et al., 2014), this effect was slightly reduced in hearing-impaired listeners at a comparable loudness. The authors underlined the striking similarity between mid-bandwidth loudness depression and relative pitch strength in normal-hearing listeners regarding their dependency on bandwidth. They considered a possible altered perception of pitch strength in hearing-impaired listeners as one possible reason. The dynamic range in relative pitch strength for bandpass noises was reduced in hearing-impaired listeners. Thus, it seems possible that the reduced relative mid-bandwidth pitch strength in hearing-impaired listeners may account for the reduced mid-bandwidth loudness depression.

Summary and Conclusion

This study measured the relative pitch strength of bandpass noise in normal-hearing and hearing-impaired listeners. The pitch strength was measured relative to a tone at the center frequency of the noise and at the same level as the noise. For both groups, relative pitch strength decreased with increasing bandwidth. For the normal-hearing listeners, bandwidth, center frequency, sound pressure level, and type of filtering had a significant influence on the relative pitch strength of bandpass noise. Hearing-impaired listeners tend to have a reduced dynamic range in the perception of relative pitch strength. For small bandwidths, hearing-impaired listeners tend to perceive weaker relative pitches than normal-hearing listeners. For a medium bandwidth, relative pitch strength in hearing-impaired listeners differed significantly from normal-hearing listeners. This observation cannot be explained with pathologically widened auditory filters in hearing-impaired listeners. Deficits in the use of TFS cues should be considered.

Acknowledgments

The authors would like to thank Dr. Florian Völk for providing them with the information and software on Filter B as well as Christopher Plack and two anonymous reviewers for thoughtful comments on an earlier version of this article.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was partly supported by the Deutsche Forschungsgesellschaft (SFB/TRR 31).

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