Acoustic Stimulation Treatments Against Tinnitus Could Be Most Effective when Tinnitus Pitch Is within the Stimulated Frequency Range

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Abstract

Acoustic stimulation with hearing aids or noise devices is frequently used in tinnitus therapy. However, such behind-the-ear devices are limited in their high-frequency output with an upper cut-off frequency of approximately $5-6\,\mathrm{kHz}$. Theoretical modeling suggests that acoustic stimulation treatments with these devices might be most effective when the tinnitus pitch is within the stimulated frequency range. To test this hypothesis, we conducted a pilot study with 15 subjects with chronic tinnitus. Eleven subjects received hearing aids and four subjects noise devices. Perceived tinnitus loudness was measured using a visual analog scale, and tinnitus-related distress was assessed using the Tinnitus Questionnaire. After six months of device usage, reductions of perceived tinnitus loudness were seen only in subjects with a tinnitus pitch of less than 6 kHz. When subjects were grouped by tinnitus pitch, the group of patients with a tinnitus pitch of less than 6 kHz ($n = 10$ subjects) showed a significant reduction in perceived tinnitus loudness (from 73.4 ± 6.1 before to 56.4 ± 7.4 after treatment, $p = 0.012$), whereas in subjects with a tinnitus pitch of 6 kHz or more ($n = 5$ subjects) tinnitus loudness was slightly increased after six months of treatment (65.0 ± 4.7 before and 70.6 ± 5.9 after treatment), but the increase was not significant ($p = 0.063$). Likewise, tinnitus-related distress was significantly decreased in the low-pitch group (from 31.6 ± 4.3 to 20.9 ± 4.8, $p = 0.0059$), but not in the group with high-pitched tinnitus (30.2 ± 3.3 before and 30.0 ± 5.1 after treatment, $p = 1$). Overall, reductions in tinnitus-related distress in our study were less pronounced than those reported for more comprehensive treatments. However, the differences we observed between the low- and the high-pitch group show that tinnitus pitch might influence the outcome of acoustic

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stimulation treatments when devices with a limited frequency range are used.

Introduction

Tinnitus, the perception of a phantom sound in the absence of a corresponding external acoustic stimulus, is a frequent phenomenon; its prevalence in adults is estimated to be about $10-15\%$ (Hoffman and Reed, 2004; Henry et al., 2005). In most cases, tinnitus is not experienced as bothersome, but for about $1-2\%$ of the population, tinnitus symptoms seriously affect the quality of life (Axelsson and Ringdahl, 1989; Pilgramm et al., 1999). Several lines of evidence point to a relation between tinnitus and hearing loss: The majority of tinnitus patients have a certain degree of hearing loss (Axelsson and Ringdahl, 1989; Nicolas-Puel et al., 2002), the hearing thresholds of subjects with tinnitus have been reported to be elevated compared to age-matched controls (Roberts et al., 2008), and signs of limited cochlear deafferentation could be demonstrated in subjects with normal audiograms and tinnitus (Weisz et al., 2006). Furthermore, the slopes of the audiograms of subjects with noise-induced hearing loss and tinnitus have been found to be significantly steeper than those of subjects with noise-induced hearing loss without tinnitus (König et al., 2006). Finally, the perceived pitch of the tinnitus sensation usually corresponds to frequencies where hearing is impaired (Henry et al., 1999; Noreña et al., 2002; König et al., 2006; Roberts et al., 2008).

Imaging studies suggest that tinnitus sensations are linked to aberrant neuronal activity in the central auditory system (Giraud et al., 1999; Lockwood et al., 2001; Weisz et al., 2005, 2007). In animal models, such aberrant activity patterns can be triggered through acoustic trauma or ototoxic drugs that induce hearing loss. After cochlear damage, increased spontaneous firing rates have been found in the dorsal cochlear nucleus (Kaltenbach and McCaslin, 1996; Brozoski et al., 2002), the inferior colliculus (Ma et al., 2006; Dong et al., 2009; Mulders and Robertson, 2009), and the auditory cortex (Noreña and Eggermont, 2003, 2006). However, which plasticity mechanisms contribute to the development of such hyperactivity has remained unclear.

Modeling studies indicate that the development of tinnitus-related neuronal hyperactivity after hearing loss could be a side-effect of activity stabilization through homeostatic plasticity in central auditory neurons (Schaette and Kempter, 2006; Dominguez et al., 2006; Schaette and Kempter, 2008, 2009): After hearing loss, auditory nerve activity is reduced, and therefor neu-

rons in the central auditory system receive less excitatory input. When the resulting decrease in mean activity activates mechanisms of homeostatic plasticity, excitation is increased and inhibition is decreased. The resulting increase in the response gain of neuronal circuits in the central auditory system restores neuronal activity to normal levels in the model. However, as a secondary effect, the neurons start amplifying spontaneous activity and thus develop tinnitus-related hyperactivity. Hyperactivity patterns predicted from audiograms of subjects with noise-induced hearing loss and tone-like tinnitus are consistent with the tinnitus pitch perceived by the subjects (Schaette and Kempter, 2009). The homeostasis-hyperactivity model suggests that additional stimulation could reverse the development of hyperactivity (Schaette and Kempter, 2006). This hypothesis is supported by the fact that in cats that experienced acoustic trauma, continuous exposure to an enhanced acoustic environment that provided additional stimulation in the frequency range of hearing loss could prevent the development of hyperactivity in the auditory cortex (Noreña and Eggermont, 2006).

Thus, for tinnitus that is associated with mild to moderate hearing loss, it should be possible to achieve a reduction of perceived tinnitus loudness when auditory nerve activity is increased through additional acoustic stimulation. Stimulation could for example be delivered through behind-the-ear hearing aids or noise devices. These devices are in widespread use in tinnitus therapy, and studies using hearing aids or noise devices have generally reported improvements in tinnitus in approximately half to two thirds of the patients (Surr et al., 1985; Folmer and Carroll, 2006; Trotter and Donaldson, 2008), but the origin of this heterogeneity was unclear. However, an important aspect that has not yet been accounted for is that behind-the-ear devices (most hearing aids and noise generators) are limited in their frequency range; typically, they produce sufficient output only up to approximately $5-6\,\mathrm{kHz}$ (Moore, 2007). Therefore, subjects with high-pitched tinnitus might not receive acoustic stimulation in the frequency range in which the tinnitus pitch is located, possibly limiting the therapeutic effects. In this study, we investigate the resulting hypothesis that acoustic stimulation through behind-the-ear devices might have a greater effect on perceived tinnitus loudness and tinnitus-related distress when the tinnitus pitch is located within the stimulated frequency range.

Methods

Subjects

Fifteen subjects (11 male, 4 female, mean age 51.7 years) with a primary complaint of chronic tinnitus (duration longer than 3 months) were recruited. Drug therapy was either not successful or not administered. Subjects with conductive or retrocochlear hearing loss were excluded. Also excluded were subjects with Meniere's disease, patients showing evidence of flow-limiting stenosis in carotid duplex, patients with signs of degenerative diseases of the cervical spine, and patients with temporomandibular joint disorder of bruxism. These exclusion criteria were chosen to avoid possible confounding factors. This study was approved by the ethics committee of the Charité.

Audiometry and Tinnitus Pitch Matching

Pure-tone audiometry was performed with a clinical audiometer calibrated to accepted standards (American National Standards Institute. Specifications for audiometers, S3.6. New York; American National Standards Institute, 1969).

To determine the tinnitus pitch, a set of pure tones (0.125, 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) was used as comparison stimuli for tone-like tinnitus, and a set of narrow-band noises centered at the same frequencies was used to assess noise-like tinnitus. The pure tones and narrow-band noises were generated using the audiometer and presented at approximately 10 dB SL. The subjects were asked which of the comparison sounds was most similar in pitch to the dominant pitch of their tinnitus sensation. Sounds were presented repeatedly and varied by the experimenter until the subject indicated a close match to the pitch of the tinnitus. Comparison sounds were presented to the contralateral ear for unilateral tinnitus, and for subjects with bilateral tinnitus, both ears were tested separately. Octave confusion was checked at the frequency one octave higher than the final pitch-matched frequency, then at the frequency one octave lower (only if these test frequencies were available).

Tinnitus pitch matching was usually performed at each appointment (see Table 1 for the number of pitch matches for each subject). The average tinnitus pitch μ_p was calculated by taking the geometric mean of the n individual pitch matches p_i, which was assigned as the 'tinnitus pitch' of a patient:

$$\mu_\mathrm{p} = \sqrt[n]{\prod_{i=1}^{n} p_\mathrm{i}} \tag{1}$$

The standard error E_{p} of the mean pitch match μ_{p} was calculated in octaves:

$$E_{\mathrm{p}} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}[\log_2(p_{\mathrm{i}}/\mu_{\mathrm{p}})]^2} \tag{2}$$

Acoustic Stimulation: Hearing Aids and Noise Devices

Subjects were fitted either with a hearing aid or a noise device, depending on the severity of their hearing loss (mean audiograms of both groups are shown in Fig. 1a). All subjects were instructed to use the hearing aid or noise device for at least 6 hours per day. Hearing aids were fitted using a modified strategy based on the NAL-NL1 rule. For unilateral hearing loss, one hearing aid was fitted, and for bilateral hearing loss, two were fitted. The noise devices (Siemens 'Tinnitus Control Instruments' (TCI), Siemens Audiologische Technik GmbH, Erlangen, Germany) had eight adjustable channels (0.25, 0.5, 0.75, 1, 1.5, 3, 4, and 6 kHz). By adjusting a gain factor for each channel, the spectrum of the therapeutic noise was adapted to the hearing loss in each patient individually: For each channel of the TCI, the perception threshold for this noise band was determined by varying the gain factor of the channel, with the gain for all other channels set to 0. This measurement was performed with the noise device in situ, using the Siemens Connexx software to control sound level. After the threshold had been determined for each channel separately, the gain factors were set to the measured thresholds in all channels, yielding the therapeutic noise. Noise devices were fitted to the tinnitus ear for unilateral tinnitus, and to both ears for tinnitus that was perceived in both ears or in the head. The subjects were instructed to adjust the volume of the noise to a comfortable loudness, preferentially to the volume at which it could just be perceived. The subjects were further instructed to only set the loudness in quiet, and to not increase the volume in a loud situation. The subjects could chose themselves whether the noise was masking the tinnitus or not.

Subjective Tinnitus Loudness and Tinnitus-Related Distress

Subjects were asked to rate the perceived loudness of their tinnitus on visual analog scales (VAS), with "inaudible" and "very loud" as reference points for the ends of the scale. The marks on the 100 mm VAS scales were converted to scores from $0-100$, with 0 corresponding to the "inaudible" end of the scale. Subjects were instructed to rate the tinnitus loudness according to how loud they perceived their tinnitus when the devices were switched off.

Tinnitus-related distress was assessed using a German version of the Tinnitus Questionnaire (Tinnitus-Fragebogen, Goebel and Hiller, 1994), where the resulting tinnitus-distress scores range from $0-84$. Distress scores from $0-30$ are considered as 'mild', $31-46$ as 'moderate', $47-59$ as 'severe', and $60-84$ as 'extremely severe' (Table 1).

Treatment Schedule

All subjects underwent an initial examination, audiometry, and tinnitus assessment (pitch matching, tinnitus questionnaire, and VAS loudness rating) on the first appointment prior to receiving their treatment device. On the first visit, a counseling session of approximately 30 minutes was performed, where also the rationale for using acoustic stimulation against tinnitus was explained. On the follow-up visits after 1, 2, 3, and 6 months, they underwent, again, audiometry and tinnitus assessment, and they also received additional short counseling sessions ($10-15$ minutes). If necessary, the behind-the-ear devices were re-adjusted.

Data Analysis

To calculate significances, the Wilcoxon signed-rank test was used for differences before and after treatment within a group and the Wilcoxon rank-sum test for comparison across groups. Errors were expressed as $\pm$ standard error of the mean. Cohen's d was calculated to quantify effect sizes. All data analysis was performed using MATLAB (The Math Works, Natick, Massachusetts).

Results

We examined the effects of prolonged acoustic stimulation on perceived tinnitus loudness and tinnitus-related distress in 15 subjects. Eleven subjects with hearing loss were fitted with behind-the-ear hearing aids, and four subjects with little or no hearing loss received behind-the-ear noise generators. Mean audiograms are shown in Fig. 1a. There were no significant differences in tinnitus pitch, initial tinnitus loudness, and initial tinnitus-related distress between the hearing-aid and the noise-device group ($p = 0.97$, $p = 0.97$, and $p = 0.44$, respectively, Wilcoxon rank-sum test). Subjects were instructed to use the devices at least 6 hours per day for six months. Table 1 summarizes the obtained tinnitus pitch, tinnitus loudness, and tinnitus-related distress for all subjects.

Analyzing all subjects as a single group after six months of acoustic stimulation, we found that the self-rated tinnitus loudness was reduced from 70.6 ± 4.5 to 61.1 ± 5.5 (Fig. 2a,c), but the reduction was not significant ($p = 0.15$, Wilcoxon signed-rank test). Tinnitus-related distress, on the other hand, was significantly reduced from 31.1 ± 3.0 to 23.9 ± 3.7 ($p = 0.016$, Wilcoxon signed-rank test, Fig. 3a,c; Table 2).

As behind-the-ear devices are limited in their frequency range (upper cut-off $\approx 5-6$ kHz, Moore, 2007), we had hypothesized that subjects with a tinnitus pitch within the frequency range of the devices would benefit more from the acoustic stimulation than subjects with a tinnitus pitch outside of the stimulated frequency range. Indeed, a closer analysis of the data from individual subjects revealed that reductions in perceived tinnitus loudness were confined to subjects with a tinnitus pitch of less than 6 kHz (Fig. 2b), supporting our hypothesis.

For further quantification of the effect, we thus grouped subjects by tinnitus pitch: the first group comprised tinnitus pitch of less than 6 kHz, and the second group comprised tinnitus pitch from 6 kHz up. There were no significant differences in tinnitus loudness or distress between the two groups before treatment ($p = 0.46$ for loudness and $p = 0.93$ for distress, Wilcoxon rank-sum test), and there were also no significant differences in age (mean ages 53.2 ± 2.8 and 48.6 ± 8.4 years, $p = 0.75$, Wilcoxon rank-sum test) or hearing loss (Fig. 1b, $p > 0.05$ for all frequencies, Wilcoxon rank-sum test).

In the group with low-pitched tinnitus (< 6 kHz, $n = 10$), self-rated tinnitus loudness was decreased from 73.4 ± 6.1 to 56.4 ± 7.4 (red bars in Fig. 2c), and the decrease was significant ($p = 0.012$, Wilcoxon signed-rank test). In the group of subjects with high-pitched tinnitus ($\geq$ 6 kHz, $n = 5$), on the other hand, self-rated tinnitus loudness increased slightly from 65.0 ± 5.4 to 70.6 ± 5.9 (blue bars in Fig. 2c), but the increase was not significant ($p = 0.063$, Wilcoxon signed-rank test). A comparison of the two groups showed that the difference in the change of tinnitus loudness was significant ($p = 0.0020$, Wilcoxon rank-sum test, Fig. 2d, Table 2).

Tinnitus-related distress was significantly decreased from 31.6 ± 4.3 to 20.9 ± 4.8 in the group with tinnitus pitch less than 6 kHz ($p = 0.0059$, Wilcoxon signed-rank test, red bars in Fig. 3c). In the group of subjects with tinnitus pitch of 6 kHz or more, on the other hand, tinnitus-related distress was unchanged (30.2 ± 3.3 before and 30.0 ± 5.1 after 6 months, blue bars in Fig. 3c, $p = 1$, Wilcoxon signed-rank test). Comparing the two groups, we found that the difference in the change of tinnitus-related distress failed to achieve significance ($p = 0.11$,

Wilcoxon rank-sum test, Fig. 3d). Taken together, our data on loudness and distress indicate that subjects with a tinnitus pitch < 6 kHz profited more from the acoustic stimulation treatment than subjects with a tinnitus pitch ≥ 6 kHz.

Changes in tinnitus-related distress were correlated to changes in perceived tinnitus loudness ($r = 0.44$), but the correlation failed to achieve significance ($p = 0.14$). This was mostly due to the fact that for some subjects, distress was decreased although loudness was unchanged. However, perceived tinnitus loudness is only one of the factors that contribute to tinnitus-related distress.

As subjects were seen after 1, 2, 3, and 6 months of treatment, we could also analyze the time course of tinnitus loudness and distress (Fig. 4). The biggest changes took place in the first two months of device usage, suggesting a time constant of weeks for the effects of acoustic stimulation.

Discussion

In this study, we tested the hypothesis that tinnitus pitch is an additional factor that influences the outcome of acoustic stimulation when devices with a limited frequency range are used to deliver acoustic stimulation. More specifically, our hypothesis was that the effects of acoustic stimulation treatment should be most pronounced in subjects with a tinnitus pitch within the stimulated frequency range. Acoustic stimulation was delivered by behind-the-ear devices, which have a steep drop-off in their output above $\approx 5-6$ kHz (Moore, 2007). After six months of device usage, decreases in perceived tinnitus loudness were observed only in subjects with a tinnitus pitch of less than 6 kHz ($n = 10$), whereas for subjects with a higher tinnitus pitch ($n = 5$), tinnitus loudness was unchanged or even slightly increased (Table 2, Fig. 2). Thus, only subjects with a tinnitus pitch within the stimulated frequency range showed a decrease in perceived tinnitus loudness.

The validity of our results depends on the reliability of the tinnitus pitch matching procedure. Tinnitus pitch matching to pure tones can yield variable results (Penner, 1983; Burns, 1984; Henry, 2004) as tinnitus sensations are often complex sounds, and the variability can also depend on the measurement method (Tyler and Conrad-Armes, 1983). The pitch-matching procedure used in our study required subjects to compare the dominant pitch of the tinnitus sensation to a set of pure tones or narrow-band noises and choose the closest match. The tinnitus

pitch-matching procedure was repeated at each appointment to account for the variability. We found that some of our subjects were very reliable, and they repeatedly matched their tinnitus to the same frequency, whereas others showed a greater variability. The biggest standard error of the mean tinnitus pitch match that we observed was 0.43 octaves (Table 1). For the analysis of the effects of acoustic stimulation, subjects were grouped according to their average tinnitus pitch matches. One way to circumvent the variability of matching tinnitus pitch to a single frequency would be to use the tinnitus spectrum approach (Noreña et al., 2002). Moreover, it might be advised to extend the frequency range for tinnitus pitch matching, as for example subject SD always matched his tinnitus pitch to 8 kHz, the highest comparison frequency in our study, indicating that his true tinnitus pitch might have been even higher. However, for our purposes, we only needed to know whether a subject falls into the high- or the low-pitch group, which could be established with a high degree of certainty through repeated matching. Moreover, even when subject KA, the responder with the highest tinnitus pitch in the low-pitch group, is moved to the high-pitch group, the difference between the groups is still significant.

Other studies reported that after receiving a hearing aid, one half (Surr et al., 1985) to two thirds (Trotter and Donaldson, 2008) of the tinnitus subjects reported improvement of their tinnitus. The subjects were not grouped according to tinnitus pitch in these studies. Decreases in perceived tinnitus loudness as reported by Folmer and Carroll (2006) for hearing aid users (reduction from 7.5 to 6.3 on a scale from 0 to 10) and noise-device users (from 7.6 to 6.2) are comparable to the change in tinnitus loudness in our subjects (mean reduction from 70.6 to 61.1 on a scale from 0 to 100). However, when we consider only the group with low-pitched tinnitus, the reduction that we observed was larger (from 75.4 to 57.1), indicating that acoustic stimulation with behind-the-ear devices might be most effective for subjects whose tinnitus pitch falls into the stimulated frequency range. Interestingly, clinical studies on the 'Neuromonics' tinnitus treatment, where the therapeutic sound covers frequencies up to 12 kHz, reported a reduction of Tinnitus Reaction Questionnaire scores of at least 40% for more than 80% of the participants (Davis et al., 2007, 2008). Our results indicate that the extended frequency range of their treatment device could have contributed to such a high success rate, as the therapeutic sound might have reached even very high-pitched tinnitus.

Moffat et al. (2009) examined the influence of hearing aids on the tinnitus spectrum, i.e. the sound characteristics of the tinnitus. They found an influence only at low frequencies, and ex-

tending the bandwidth of the hearing aids did not lead to additional effects. However, perceived tinnitus loudness and tinnitus-related distress were not assessed in this study, and thus their results cannot be directly compared to ours. Ideally, a future study would combine measurements of the sound characteristics of tinnitus (e.g. tinnitus spectrum), loudness measurements (e.g. minimal masking levels), subjective tinnitus loudness (e.g. visual analog scales) and assessment of tinnitus-related distress (e.g. Tinnitus Questionnaire, Tinnitus Handicap Inventory). An additional factor that would need to be taken into account for future studies of acoustic stimulation against tinnitus are cochlear dead regions, which are frequently encountered for moderate-to severe hearing loss (Vinay and Moore, 2007).

In our study, we employed a restricted tinnitus therapy, consisting of short counseling sessions and fitting of hearing aids or noise devices. Consequently, we only achieved $20-30\%$ reduction of the tinnitus loudness and distress scores. More comprehensive approaches, like for example cognitive behavioral therapy (Hiller and Haerkötter, 2005), Neuromonics (Davis et al., 2008), or tinnitus retraining therapy (Jastreboff and Jastreboff, 2000) led to larger changes in tinnitus characteristics. However, our goal was not to demonstrate a new, more effective tinnitus therapy, but to identify an additional factor that might influence the outcome of acoustic stimulation treatments.

The fact that in our study only subjects with a tinnitus pitch within the stimulated frequency range showed a reduction of perceived tinnitus loudness suggests that an interaction of acoustic stimulation with the tinnitus-generating neurons might have taken place. Possibly, the additional acoustic stimulation could have caused a decrease of neuronal response gain in the stimulated frequency channels. Computational modeling indicates that such a decrease in response gain could also reduce tinnitus-related hyperactivity (Schaette and Kempter, 2006). Changes reminiscent of decreased response gain have been observed in humans, where long-term exposure to low-level noise (Formby et al., 2003), long-term hearing aid use (Olsen et al., 1999; Philibert et al., 2002), and exposure to an enriched acoustic environment designed to compensate for the decrease in auditory input after hearing loss (Noreña and Chery-Croze, 2007) decreased the perceived loudness of sounds. Further support for physiological changes in the auditory system in dependence upon the level of sensory input comes from the finding that unilateral earplug-induced sensory deprivation lowers the acoustic reflex threshold in the plugged ear (Munro and Blount, 2009).

Ultimately, the success of any acoustic stimulation strategy against tinnitus depends on whether stimulation can be delivered effectively, which is determined not only by the output characteristics of the treatment device, but also by the kind and degree of hearing loss. Our results indicate that the probability of achieving a reduction in perceived tinnitus loudness might be higher when the tinnitus pitch is located within the frequency range of the treatment device. However, they were obtained with a relatively small sample of 15 subjects that showed only mild to moderate distress. How well the results will generalize, for example to severely distressed subjects or to subjects with more severe hearing loss, remains to be evaluated in a larger study. Nevertheless, we hope that our results will contribute to the development of effective acoustic stimulation strategies against tinnitus.

List of Abbreviations

Hearing aid - HA

Noise device - ND

Tinnitus questionnaire - TQ

Visual analog scale - VAS

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Table 1: Overview of all 15 subjects. Tinnitus pitch is given as the average (geometric mean) of repeated tinnitus pitch matching sessions (in units of kHz), whereas the standard error of the mean is given in octaves. HA = hearing aid, ND = noise device. Tinnitus-related distress (TQ score, $0-84$), and tinnitus loudness ($0-100$) were rated before treatment (initial) and after treatment (6 months).

Subject	Tinnitus pitch [kHz $\pm$ octaves]		Number of matchings	Treatment device	TQ score		Loudness	
	left	right			initial	6 months	initial	6 months
BHJ	3.29 ± 0.42	2.86 ± 0.3	5	ND	34	28	80	84
BM		0.57 ± 0.37	5	ND	37	30	91	65
DA		0.97 ± 0.26	5	HA	35	7	50	29
FJ	8	8	1	HA	38	48	77	82
FC		3.44 ± 0.2	5	HA	26	6	66	47
HH	1.11 ± 0.15		4	HA	13	12	69	67
KA	5.83 ± 0.37	5.42 ± 0.43	4	ND	42	20	55	50
KM	6.93 ± 0.12		4	HA	29	27	73	83
KG	4.76 ± 0.25	4.76 ± 0.25	4	HA	21	8	47	11
KKD	2 ± 0		5	HA	38	29	100	52
RV	3.17 ± 0.33	3.17 ± 0.33	3	HA	13	14	78	78
RB	1.3 ± 0.2		5	HA	57	55	98	81
SD	8 ± 0	8 ± 0	4	ND	27	17	50	57
ST	6 ± 0		4	HA	20	26	71	75
VA		7.67 ± 0.24	4	HA	37	32	54	56

Table 2: Analysis of changes of tinnitus-related distress (TQ score) and perceived tinnitus loudness (Loudness) in dependence upon tinnitus pitch. *p*-values are for Wilcoxon signed-rank tests, and Cohen's *d* was calculated to quantify effect sizes.

Group	*n*	Measure	Before treatment	After 6 months	*p*-value	Effect size
All	15	TQ score	31.1 ± 3.0	23.9 ± 3.7	0.016	0.57
		Loudness	70.6 ± 4.5	61.1 ± 5.5	0.15	0.51
Tinnitus pitch	10	TQ score	31.6 ± 4.3	20.9 ± 4.8	0.0059	0.78
< 6 kHz		Loudness	73.4 ± 6.1	56.4 ± 7.4	0.012	0.83
Tinnitus pitch	5	TQ score	30.2 ± 3.3	30.0 ± 5.1	1	0.02
≥ 6 kHz		Loudness	65.0 ± 5.4	70.6 ± 5.9	0.063	-0.49

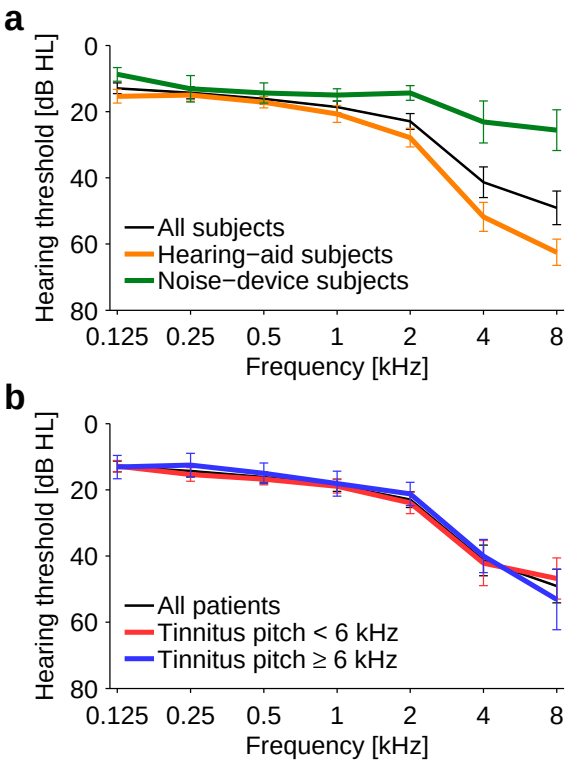

Figure 1: Mean audiograms. **a)** Patients grouped by treatment device: all patients (black line), patients fitted with hearing aids (orange line), and patients fitted with noise devices (green line). **b)** Patients grouped by tinnitus pitch: all patients (black line), patients with a tinnitus pitch < 6 kHz (red line), and patients with a tinnitus pitch ≥ 6 kHz (blue line).

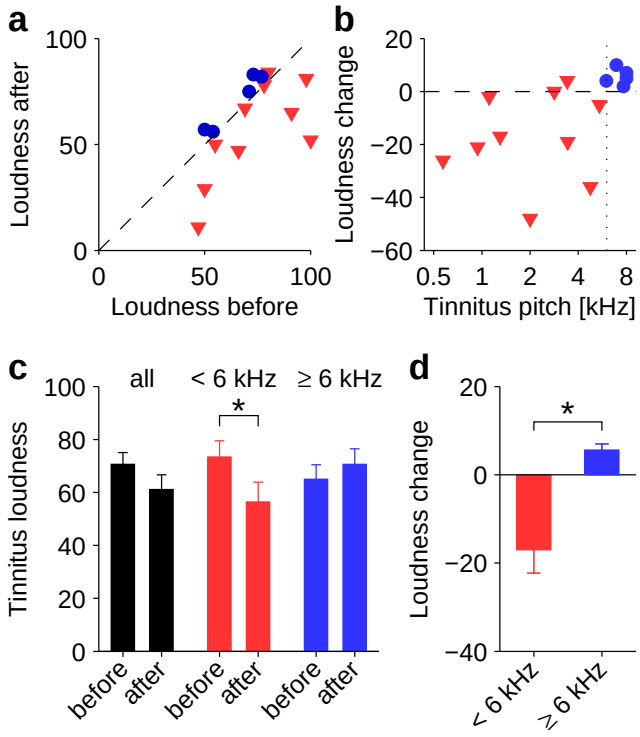

Figure 2: Effect of acoustic stimulation on perceived tinnitus loudness, which was measured on a visual-analog scale (converted to scores from $0-100$). **a)** Self-rated tinnitus loudness of 15 subjects before and after six months of treatment. Red triangles: subjects with a tinnitus pitch of less than 6 kHz (<6 kHz, $n=10$); blue circles: tinnitus pitch of 6 kHz or more (≥ 6 kHz, $n=5$). The dashed black line is the identity line. **b)** Change of tinnitus loudness versus tinnitus pitch. **c)** Group averages of tinnitus loudness before and after treatment. Only the group of subjects with a tinnitus pitch of <6 kHz experienced a significant decrease in tinnitus loudness ($p=0.012$). **d)** Mean change of perceived tinnitus loudness. The difference between the group of subjects with a tinnitus pitch of <6 kHz and the group with a tinnitus pitch of ≥ 6 kHz was significant ($p=0.0020$).

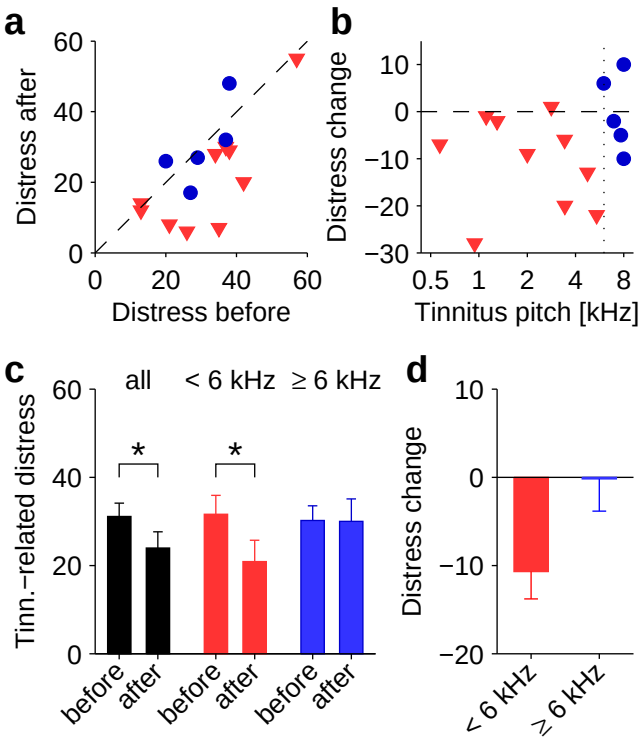

Figure 3: Effect of acoustic stimulation on tinnitus-related distress, which was assessed using the Tinnitus Questionnaire (scores range from $0-84$). **a)** Tinnitus-related distress of 15 subjects before and after six months of treatment. Red triangles: subjects with a tinnitus pitch of less than 6 kHz (<6 kHz, $n=10$); blue circles: tinnitus pitch of 6 kHz or more (≥ 6 kHz, ($n=5$). The dashed black line is the identity line. **b)** Change of tinnitus-related distress versus tinnitus pitch. **c)** Group averages of tinnitus-related distress before and after treatment. Significant reductions of distress were seen when all subjects were analyzed as a single group ($p=0.016$), and in the subgroup with a tinnitus pitch of <6 kHz ($p=0.0059$). **d)** Mean change of tinnitus-related distress.

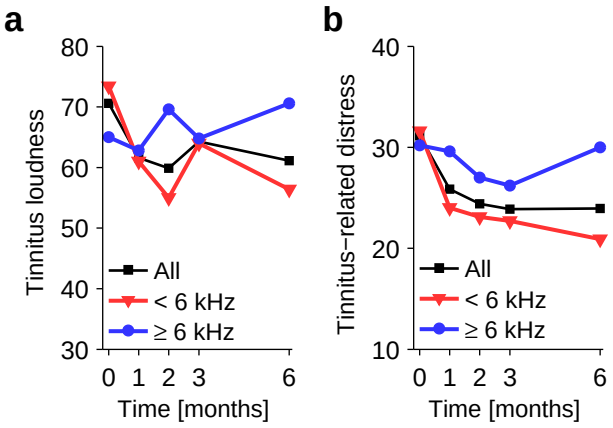

Figure 4: Time courses of perceived tinnitus loudness (**a**) and tinnitus-related distress (**b**), group averages. Black squares: all subjects; red triangles: tinnitus pitch less than 6 kHz (< 6 kHz, $n = 10$); blue circles: tinnitus pitch 6 kHz or more (≥ 6 kHz, $n = 5$).