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Research Paper

Choice of test stimulus matters for pitch matching performance: Comparison between pure tone and narrow band noise

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ABSTRACT

Chronic tinnitus, a symptom of high prevalence, is a persistent hearing sensation in the absence of an external sound source. Recent electrophysiological studies indicate that tinnitus generation is to a high degree the result of maladaptive plasticity in the central auditory pathway. The pitch of the tinnitus sensation can be assessed by performing a pitch matching procedure. In the most frequent "tonal tinnitus" type pure tones are used as test stimuli. However, in the case of tonal tinnitus not a single malfunctioning neuron, but rather a population of neighbouring neurons is involved in the generation process of tinnitus and patients typically perceive their tinnitus as a sound having a prominent centre frequency with some spectral extent. Thus, the question arises, why not to use narrow band noise (NBN) instead of pure tones as test stimuli in pitch matching procedures? To investigate this, we first evaluated the pitch matching performance of healthy subjects. In a recursive two alternative choice testing, driven by a computer based automated procedure, the subjects were asked to match the pitch of two sounds. In a crosswise design, NBNs and pure tones were used both as target and as test stimuli. We were able to show that across all four possible combinations the pitch matching performance was least favourable when a sinusoidal sound had to be matched to an NBN target. Even though matching two sinusoidal sounds results in the lowest error, considering that the tinnitus percept typically includes some spectral extent, an NBN should be preferably used as a test stimulus against a pure tone.

1. Introduction

Chronic tinnitus is one of the most common auditory disorders affecting more than 10% of the general adult population (Heller, 2003). Unfortunately, incidence and prevalence rates of tinnitus currently increase not only in older people, but also in young adults, a fact which might be associated with intensive exposure to loud music in an occupational or recreational environment (Eggermont and Roberts, 2012; Okamoto et al., 2011). Tinnitus as a prevalent symptom/syndrome can severely affect a patient's ability to lead a normal life. Depending on whether the patients perceive it as a trivial or debilitating condition, it could result in comorbid psychiatric disorders. In most cases tinnitus is a persistent sensation of sound in the absence of an external sound source and therefore it is considered to be a subjective phantom sensation. Tinnitus may be perceived uni- or bilaterally and may occur intermittently or continuously, while its quality varies on inter- and intra-individual bases (Davis and Refaie, 2000; Luxon, 1993; REED, 1960). Tinnitus patients describe it as tonal (whistling, ringing, chirping), noise like (hissing steam, rushing water, ocean waves) or a fluctuating mixture of those (Eggermont, 2012). In cases when tinnitus resembles a sinusoidal tone, it is denoted as *tonal tinnitus* (Langguth et al., 2017). Tinnitus is often associated with hearing loss, but it can also occur in normal hearing (Kim et al., 2011).

Recent findings based on animal models of tinnitus and research on tinnitus patients (Eggermont, 2012; Eggermont and Roberts, 2015; Pantev et al., 2012; Roberts et al., 2010) indicate that tinnitus is the result of maladaptive plasticity in the central auditory pathway. Most often, cochlear damage leads to a disturbed

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excitation-inhibition balance in the central auditory pathway, triggered by a deprivation of auditory neural input (Feldman, 2009; Turrigiano, 2008). As a consequence, weakened inhibitory networks initiate reorganization processes that yield increased spontaneous firing rates of neurons in auditory subcortical and cortical structures as well as in the auditory cortex representation (Møller, 2007; Pantev et al., 2012). Thus, it seems that the main reason for development and manifestation of the tinnitus sensation is the lack of inhibition driving a malfunctioning of specific populations of auditory neurons (Pantev et al., 2012). In order to effectively cure tinnitus, the affected neurons have to be identified and targeted. Magnetoencephalographic studies reveal an enhanced activity for auditory cortical areas corresponding to the tinnitus frequency (Diesch et al., 2004; Okamoto et al., 2010) while additionally, the underlying auditory cortical maps seem to be distorted (Mühlnickel et al., 1998). Thus, especially in patients suffering from tonal tinnitus, a precise determination of the tinnitus pitch is of extreme importance for both research as well as treatment (Henry and Meikle, 2000).

Currently, audiologists perform the assessment of tinnitus pitch. In order to quantify the tinnitus sensation, its auditory perceptual attributes like pitch, loudness and spectral content have to be determined. Since there is presently no objective measurement of those tinnitus parameters, their identification purely relies on the patient's subjective report. In order to determine the tinnitus pitch characteristics, in the case of tonal tinnitus, a pitch matching procedure is applied. Thereby, the frequency of an externally presented sound is varied until patients indicate the perception of a sound akin to their tinnitus sensation. In a clinical environment, normally the outcome of a single pitch matching is regarded as the tinnitus frequency. Performing repeated pitch matchings typically results in a poor reliability since the responses might vary over 2-3 octaves (Burns, 1984; Henry et al., 2004; Penner, 1983). A possible reason for that could be that tinnitus is not experienced as a pure tone, but as a combination of sounds with close spectral content (Norena et al., 2002; Roberts et al., 2008).

In contrast to the traditional procedure employing a sinusoidal sound as test stimulus, more recent approaches (Norena et al., 2002; Roberts et al., 2008) use several frequencies. The derived tinnitus spectrum is typically consistent with the spread of repeated pure tone presentations (Burns, 1984); Tyler and Conrad-Armes (1983). According to the study of Henry et al. (Henry et al., 2013) patients with narrow-band tonal tinnitus are more consistent in repeatedly matching the bandwidth of their tinnitus sound, when compared to those describing their percept as an intermediate noise. The majority of those patients described their perception being rather similar to the pure tone, however, with an additional spectral content.

Taking into account the hypothesis that tinnitus is caused by a malfunctioning of a population of neighbouring auditory neurons and that the experimental results mentioned above are pointing to the perception of a pure tone, with additional spectral content, the question arises whether the approach of using a narrow band noise (NBN), with adjustable centre frequency and bandwidth as a test stimulus, has an advantage over an approach based on pure tone matching. If this holds true, then it could be expected that pitch matching reliability in patients with tonal tinnitus, which is the most prominent group of tinnitus sufferers (>40% in (Al-Swiahb and Park, 2016), >75% in (Eggermont, 2003)), can be successfully increased.

This study is a first step to evaluate pitch matching performance in a sufficiently large group of control subjects not suffering from tinnitus. In a first experiment, we investigated participants' performance when matching NBN test sounds of different bandwidths to an NBN target sound of a fixed bandwidth. The bandwidth maximizing the performance was then used as the bandwidth of the NBN sounds being applied as test stimuli in the pitch matching performance evaluation in a second experiment. Here, subjects were asked to adapt the frequency of a test stimulus until their perception fits to a target stimulus. Test and target sounds are presented simultaneously and contra-laterally as external stimuli to the subject. Both pure tones and narrow band noises serve as test as well as target stimuli. The target sound is supposed to simulate the tinnitus perception. The advantage of this approach is that the "true" target pitch is known (either pure tone or NBN). This enables a better estimation of the pitch matching performance. The parameter of interest was the matching error, defined as the absolute value of the logarithm of frequency ratio of target and test sound. In order to allow the testing to be conducted rapidly and without intervention by an investigator, we developed computer-automated techniques including a graphical user interface. The outcome of this study will provide valuable input for follow-up studies on patients with tonal tinnitus.

2. Material and methods

2.1. Participants

Thirty participants from our local subject pool took part in two experiments performing a frequency-matching task. All participants claimed neither suffering from chronic tinnitus nor perceiving a tinnitus when they underwent the test procedures conducted in this study. The sample included 13 females and 17 males having a mean age of 38.1 years (range: 24–58 years, standard deviation [SD] = 11.1 years). We conducted the study according to the Declaration of Helsinki. Each participant signed an informed consent form before study enrollment.

2.2. Equipment

Subjects were seated in front of a computer monitor, wearing common stereo headphones (model: HD 201 by Sennheiser electronic GmbH, Hannover, Germany) connected to a sound card (model: Realtek High Definition Audio by RealTek, Hsinchu, Taiwan) mounted in a standard personal computer (model: Optiplex 7020 by Dell GmbH, Frankfurt a.M., Germany) running Microsoft Windows 10 Enterprise (by Microsoft Corporation, Redmond, USA). Participants gave their responses via a standard three button computer mouse. The graphical user interfaces were programmed with Matlab (Release, 2017a; Version 9.2 by Mathworks, Natick, USA) as a tailor-made software application, which we developed in our lab specifically for this study purpose. For each step of the testing procedure, the software consists of a module linked with a graphical user interface (GUI). Participants received instructions verbally by the experimenter and visually on the screen on how to operate the units of the GUIs (buttons and sliders). They were further told that the testing procedures aim to determine a pair of target and test sounds which correspond in their center frequency. The participants were guided through the application via pop-up windows. The testing did not require any additional interaction with an examiner. As a safety constraint, the software limited all signal amplitudes thus restricting the sound pressure output to non-harmful levels (<90 dB SPL). Test and target sounds were delivered via the headphones to the subject, whereby the target was always presented contra-laterally to the test sound in order to avoid generating a beat sensation.

Apart from the provision of GUIs for the test environment, the tailor-made software application enabled us to control the computer soundcard in order to deliver sinusoidal signals and NBN to the participants. An implemented NBN signal generator modified

the spectral content of a white noise in accordance to the given center frequency and spectral border frequencies via inverse fast Fourier transformation. This resulted in a rectangular NBN spectrum with the center frequency situated at the midpoint of the filter cutoffs based on an octave scale. We reviewed the sound pressure levels and spectral contents of the acoustic output signal delivered via headphones using a sound measurement and analyzer platform (type 3560), an artificial ear (type 4153) and the data recorder software (version PULSE 14.1) (all by Bruel&Kjaer, Naerum, Denmark).

2.3. Procedures

In two experiments, subjects had the task to align the perception of a test and a target sound by modifying interactively the center frequency of the test sound. We conducted the experiment in two sessions, about 6 weeks apart from each other. This was necessary since data of experiment one had to be analyzed in order to utilize their outcome for parameter settings of the second experiment (NBN test sound bandwidth).

In the following the general designs of the test protocols applied in experiment 1 and 2 are described. For a better understanding, additionally the workflow of the procedures is illustrated in Figs. 1 and 2.

2.3.1. Intensity setting of target sound based on hearing threshold

Before the actual pitch matching, we determined the individual hearing thresholds for each of the targets using a fully automated procedure provided by the software application mentioned above. The current tinnitus literature (REED, 1960; Tyler et al., 1992) suggests that the perceived loudness of tinnitus typically is between 5 and 10 dB SL at the matched frequency. In order to be clearly perceptible for persons with normal hearing, but still having a loudness being comparable to a tinnitus sensation, we presented the targets with an intensity of 20 dB SL.

2.4. Step 1: loudness adaptation

The pitch matching procedure in both experiments consisted of three steps. *First*, participants adjusted the loudness of each of the 17 test sounds (one for each quarter of an octave in the frequency range from 1 to 16 kHz) to the loudness of the target sound. Thereby, subjects adjusted the level of the test sound by changing the slider position on a GUI. As starting level for the first test sound (1 kHz) the chosen signal amplitude of the target corresponded to 20 dB SL. The starting levels for the subsequent test sound respectively corresponded to the amplitude of the preceding test signal, which the subject already matched to the loudness of the target. After participants confirmed their choice by a button press, the value was stored as default level for the test sound in order to use this setting in the further testing. The loudness matching procedure continued by increasing the center frequency of the test sound by one quarter of an octave until either the upper limit of the frequency range (16 kHz) was reached, or the participant indicated by a button press that the test sound could not be perceived anymore. For all subsequent modules of the matching procedure, we decreased the step size of the center frequencies from a quarter to 1/12 of an octave. We derived the missing values for the matched level from interpolating between the values determined before.

2.5. Step 2: frequency matching

In step 2 the participants performed a frequency matching of test and target sounds based on the recursive two-alternative forced choice paradigm. (Diesch et al., 2004; Henry and Meikle, 2000; Wunderlich et al., 2015). The task for each participant was to decide in multiple iterations which test sound out of two is more similar to a continuously presented target regarding their center frequencies. Thereby, the participant had to listen at least once to each of the two test sounds. By pressing a button provided by the GUI they were able to start and stop the presentation of one of the test sounds respectively. They could repeatedly listen to either one of them as often as they like. The participants confirmed their decision by pressing another button on the GUI. The center frequencies of the test sounds were defined according to the following procedure: For the first iteration, the frequency range from 1 kHz to the upper frequency limit being determined for each subject in the loudness adaptation procedure (see below), was bisected into two equally large subintervals (based on an octave scale). Thereby, the interval borders could take only values being apart by 1/12 octave. For each of the two intervals, we presented two test sounds having center frequencies that corresponded to the lower and upper interval borders. Depending on the decisions which sounds were more similar to the target, bisection and two-interval forced-choice testing was reapplied to the low or to the high subinterval respectively to the new middle interval that was bounded by the mid-points of the low and high subintervals. For example, a 1 kHz and a 4 kHz sound defining the first, and a 4 kHz and 16 kHz sound defining the second interval were presented. If participants decided on 1 kHz for the first and 4 kHz for second interval, the interval borders of the next iteration would have been 1 and 2 kHz, and 2 and 4 kHz, respectively. We repeated this procedure until interval borders were 1/12 of an octave apart. We then noted the final selection done by the subject as outcome of the frequency matching. The testing did not require any intervention by an examiner. For the frequency matching, we adopted the amplitudes of the test signals from the preceding loudness matching in accordance to their center frequencies. The target was presented continuously with a sound level of 20 dB SL.

2.6. Step 3: octave confusion test

Finally, an octave confusion test completed the procedure. Again, we asked participants to compare the target and test sounds established in step 2 based on a two-alternative forced-choice test. Here, the interval border frequencies corresponded to the center frequency as adopted from the pitch matching applied before (step 2) and its sub- and super harmonics. Again, in an iterative procedure, subjects were asked to judge whether the higher or lower test sound was respectively more similar to the continuously presented target sound, with regard to their center frequencies. Depending on subjects' decision in the next iteration the preferred test sound had to be compared to the next higher harmonic. This procedure was finished when the center frequency of the higher test sound corresponded to the highest harmonic being located in the range from 1 kHz to the highest frequency being detectable by the individual participant (derived in the loudness matching procedure applied before). The value for the center frequency of the test sound, as derived from the last iteration, was chosen as the final result of the pitch matching procedure. Subjects performed the task via a GUI similar to the one used before.

3. Experiments

3.1. Experiment 1

The goal of the first experiment was to evaluate the NBN bandwidth on which subjects performed best, when matching two NBN sounds. As target, we applied an NBN having a fixed bandwidth of 1/32 of an octave. This value derived from the outcome of

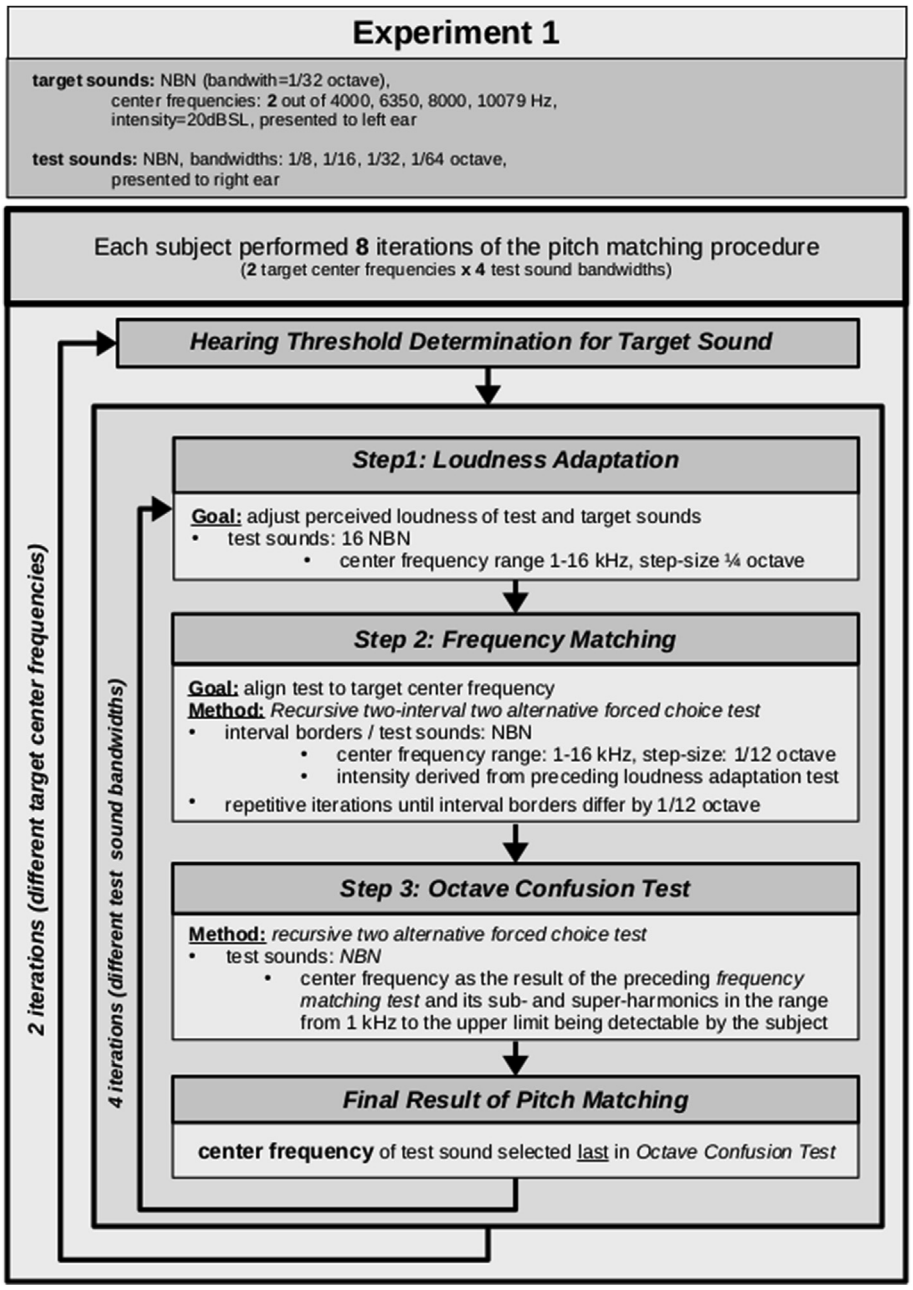

Fig. 1. Workflow of the testing protocols performed in experiment 1.

the study of Henry et al. (Henry et al., 2013), in which a group of tinnitus patients judged on the bandwidth of their tinnitus percept when performing a noise-band matching. Two out of four (4000, 6350, 8000 or 10079 Hz) target center frequencies were allocated randomly to each subject. Thus, we adequately covered the main part of the frequency range of the tinnitus sensation that typically arises in humans. For each of the target sounds we determined participants' individual hearing threshold. The bandwidth of the NBN serving as test sound could take values of 1/8, 1/16, 1/32 and 1/64 of an octave. We always presented the test sound to the right ear.

In total, each participant performed eight iterations of pitch matchings in a single session. We randomized the temporal order of the conditions (different NBN bandwidths) across subjects. The workflow of experiment 1 is illustrated in Fig. 1. Apart from determining an optimal bandwidth for the test sounds, this experiment had also the goal of preparing for experiment 2, on the outcome of which we will mainly focus.

3.2. Experiment 2

In the second experiment, we compared subjects' performance of matching the center frequencies of two sounds, which were either a pure tone (Sin) or an NBN. In a crosswise setup, the target and test sounds either matched or differed in signal type. Based on that, the target−test combinations NBN-NBN, NBN-Sin, Sin-NBN and Sin-Sin served as experimental conditions.

In the case of an NBN as target, the bandwidth was set to 1/32 of an octave. Since in the second experiment we were mainly interested in relative frequency matching errors and our focus was not to investigate how far the matching performance depends on the

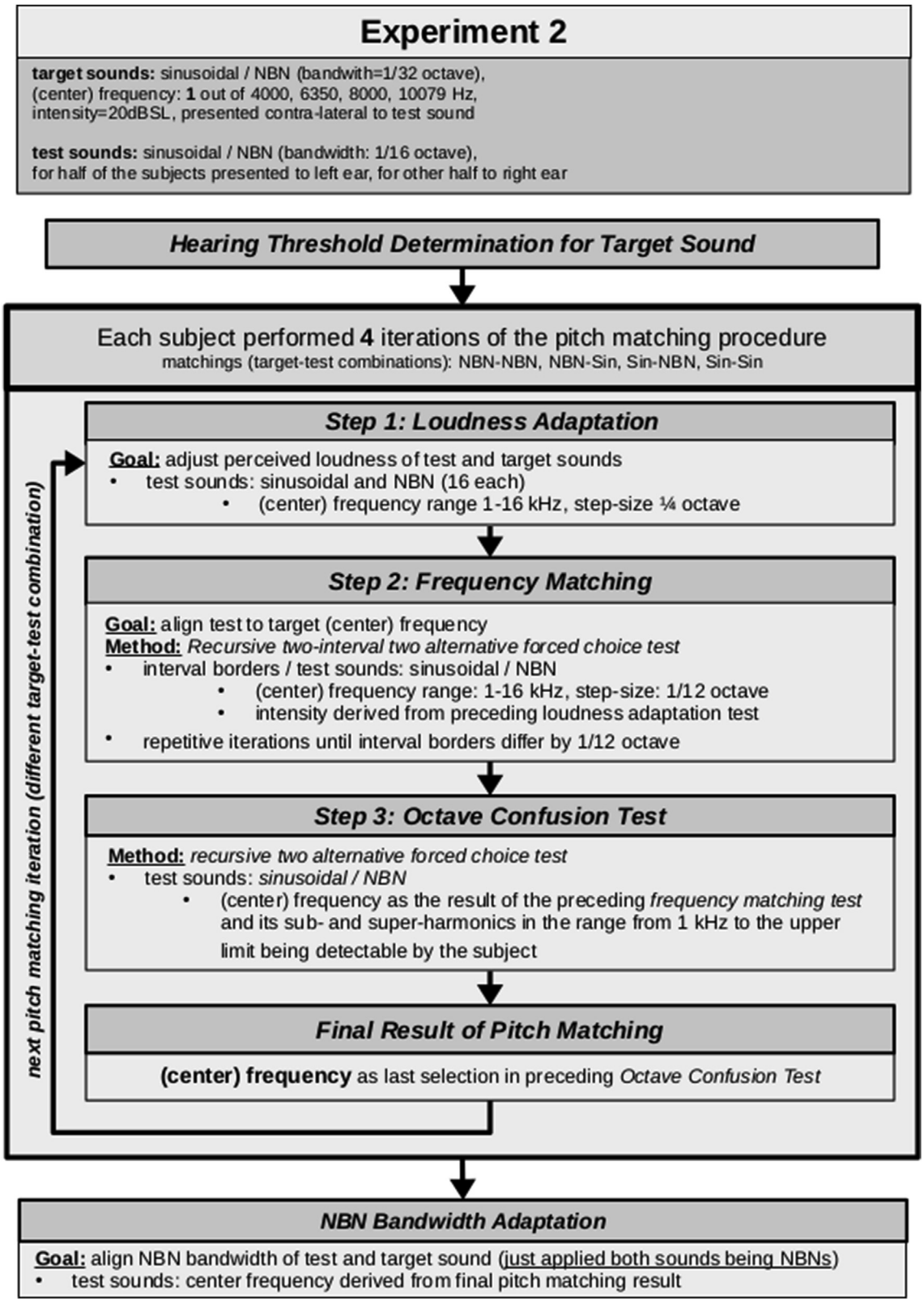

Fig. 2. Workflow of the testing protocols performed in experiment 2.

absolute value of the target center frequency, each participant performed the matching just for 1 out of 4 center frequencies (see above). Those frequencies were randomly allocated to the subjects. We further kept the number of matchings each participant had to perform, at a value being tolerable by the subjects. As in experiment 1, we determined participants' individual hearing threshold for the target sound prior to applying the pitch matching procedure.

Following the result of experiment 1, in the case in which the

test sound was an NBN bandwidth of the test sound was set to 1/16 of an octave. For half of the participants, we presented the test sound to the left ear, for the other half to the right ear. As for experiment 1 the choice was arbitrary to present the test sounds always to the right ear, here we decided for a counter balanced ear assignment in order to avoid the stimulation side having an impact on the matching performance.

Each participant performed four iterations of pitch matchings in a single session. We randomized the order of the conditions (pairs of test and target sounds) across subjects. The detailed workflow of experiment 2 is illustrated in Fig. 2.

As an additional step in experiment 2, we asked participants to adjust the bandwidth of the test sound until they perceived it as most similar to the continuously presented target sound. Thereby, as initial values we adopted the center frequencies from the preceding octave confusion test. We only applied this step, in case both signals being compared had been NBNs. The participants changed the bandwidth of the test sound by operating a slider with the computer mouse in a further GUI. Thereby, the minimal step size of a slider movement corresponded to a change in bandwidth of 1/200 octave.

3.3. Data analysis

To evaluate participants' performance in frequency matching we used as a measure the difference between center frequency of test and target sound. In order to account for the behavior of the human hearing system, we determined the matching error as the absolute value of the difference based on an octave scale using the formula:

$$matching\ error = abs\left(log2\left(\frac{CenterFreqTarget}{CenterFreqTest}\right)\right)$$

Since we were mainly interested in the absolute frequency matching error we decided to base our analysis on this value. Further on, using the original (signed) value of the difference between test and target sound frequency in group averages and statistic procedures might lead to a misinterpretation of the results, since positive and negative differences might cancel out each other and yield smaller matching errors.

3.4. Experiment 1

We analyzed the matching errors with a repeated-measures analysis of variance (ANOVA) with the two between-participant factors *center frequency* (four levels: 4000, 6350, 8000 and 10079 Hz) and *NBN bandwidth* (4 levels: 1/8, 1/16, 1/32 and 1/64 of an octave). Additionally, for each subject and matching run (two center frequencies per subject) we determined a ranking (places 1 to 4) of conditions (four NBN bandwidths) based on matching errors. In case of equal values, tied ranks were allocated. In order to test for difference in mean ranking values, we applied a one-way ANOVA with four factor levels (four bandwidths).

3.5. Experiment 2

We analyzed the data with a one-factorial ANOVA with four levels (target-test: NBN-NBN, NBN-Sin, Sin-NBN, Sin-Sin). Importantly, planned comparisons were used to test the hypothesis, that the method NBN-Sin would produce the largest frequency matching error whereas the method Sin-Sin would produce the smallest frequency matching error in comparison to all other methods. The analysis was done with IBM SPSS Statistics 25 (by IBM Corporation, New York, USA). The preplanned comparison was done using the K-Matrix procedure. As a follow-up analysis we conducted a one-factorial ANOVA with four levels representing the target center frequencies followed by multiple-comparison tests which outcome ran through a Bonferroni correction. Thereby, the pitch matching errors derived for the four different target-test sound pairs mentioned above were accumulated.

3.6. Experiment 1 and 2 (follow-up)

In order to further evaluate whether participants tended to under- or over-estimate the target frequency in a follow-up analysis we applied one-sample t-tests to the original (signed) values of the matching errors derived for the four conditions in each of the two experiments.

4. Results

All 30 subjects successfully completed the two experiments distributed over two sessions.

4.1. Experiment 1

Group results of subjects' performance matching the center frequency of NBNs having different bandwidths to target sounds having a fixed bandwidth of 1/32 octave, are shown in Fig. 3. In general, the frequency matching errors were smaller and showed less variance across individuals if target sounds had a low center frequency (e.g. 4000 Hz). As confirmation for the visual inspection, a two-factorial ANOVA revealed a significant effect of target sound center frequency on matching performance [$F_{(3,\ 239)} = 8.43$, $p < 0.001$]. After accumulating the results across the two tests, with different target center frequencies, the group matching errors resulted in values of about half of an octave ±1/16 octave (mean ± SD) (see Table 1). The two-factorial ANOVA did not show any significant impact of the test sound bandwidth [$F_{(3,\ 239)} = 0.31$, $p > 0.5$] on the matching performance.

Fig. 4 illustrates group results after ranking the four conditions (different test sound bandwidth) regarding the matching error for each session including two target center frequencies allocated to each subject. The one-way ANOVA that has been applied to the

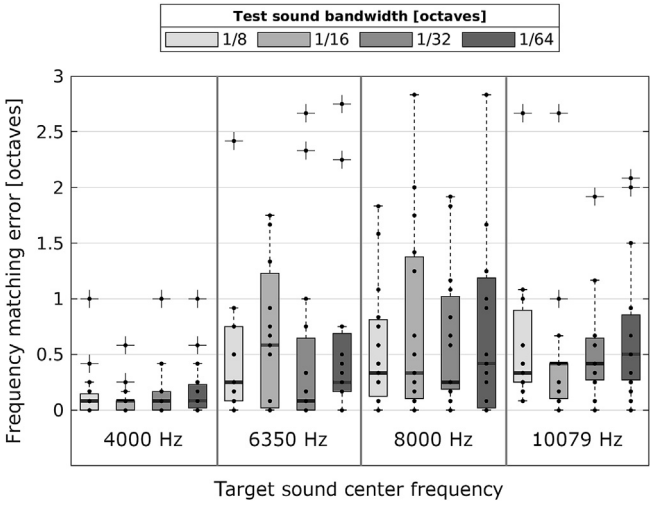

Fig. 3. (Experiment 1) Subjects' performance matching center frequencies of two narrow band noises depending on test sound bandwidth and target sound center frequency; frequency matching errors (illustrated as filled circles) represent absolute differences between center frequencies of target and test stimuli; in each box median value (centered thick line), lower and upper quantile and whisker and outliers (crosses) of the matching error are shown.

Table 1
(Experiment 1) Pitch matching performance expressed as absolute difference between center frequencies matching two sounds having different bandwidths.

Test Sound Bandwidth	1/8	1/16	1/32	1/64
Group Mean	0.467	0.501	0.506	0.556
Standard Deviation	0.567	0.682	0.615	0.699

Target sound: fixed bandwidth of 1/32 octave, center frequency: 4000, 6350, 8000 or 10079 Hz; matching results derived for different target center frequencies are accumulated; all values are expressed in octaves.

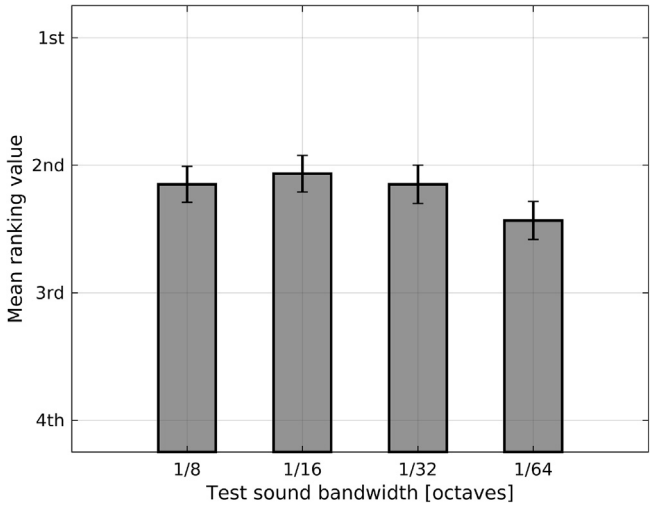

Fig. 4. (Experiment 1) Subjects' pitch matching performance expressed as mean ranking values; for each of the two matchings a ranking (place 1 to 4) of conditions (different test sound bandwidths) was determined based on matching errors (in case of equal matching errors we allocated conditions to the same place); error bars represent standard errors of the mean.

ranking values revealed again no significant impact of test sound bandwidth on matching performance [$F_{(3, 239)} = 1.21$, $p > 0.05$]. In Table 2 the mean ranking values and the corresponding standard deviations and standard errors of the mean across subjects are shown. Due to the highest mean ranking value, we selected a value of 1/16 of an octave to be used as test sound bandwidth in all further evaluations in experiment 2.

4.2. Experiment 2

Group results of subjects' performance matching two sounds, with one or both of them being a pure tone (Sin) or an NBN, are shown in Fig. 5. The one-factorial ANOVA with four levels representing the matching conditions was significant ($F_{(3, 87)} = 5.031$; $p = 0.003$). Thus, in general the pitch matching performance differed depending on the signal type of target and test sound. Testing that the condition Sin-Sin would result in the lowest matching error was applied in a preplanned manner and was

Table 2
(Experiment 1) Comparison of subjects' pitch matching performance for different test sound bandwidths expressed as mean ranking values.

Test Sound Bandwidth [octaves]	1/8	1/16	1/32	1/64
Mean Ranking Value (across subjects)	2.15	2.067	2.15	2.433
Standard Deviation	1.087	1.118	1.162	1.155
Standard Error of the Mean	0.1403	0.1443	0.15	0.1491

For each subject the condition ranking (place 1 to 4) was determined based on matching errors (in case of equal matching errors we allocated conditions to the same place).

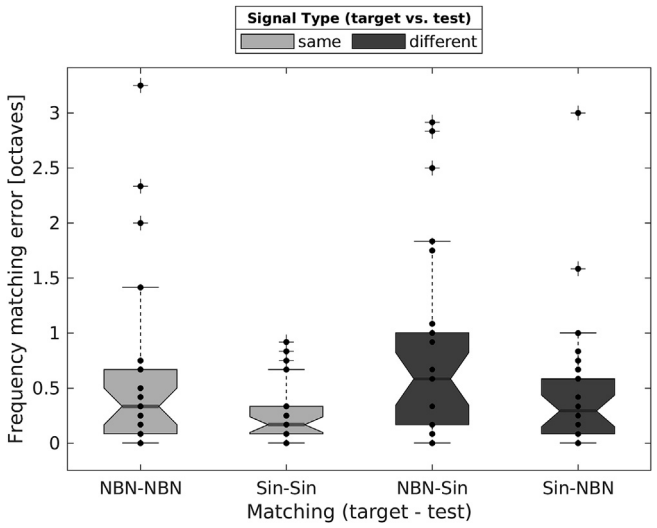

Fig. 5. (Experiment 2) Subjects' frequency matching performance depending on signal type of sounds to be matched; matching errors as absolute difference between target and test sound center frequencies are shown as filled circles; in each box median value (centered thick line), lower and upper quantile and whisker and outliers (crosses) of the matching error are shown; according to pre-planned comparison tests condition Sin-Sin resulted in lowest matching errors ($p = 0.006$) and condition NBN-Sin in largest matching error ($p = 0.003$) compared to all other conditions.

confirmed (estimation of contrast: 0.947; standard error: 0.322; $p = 0.006$). As hypothesized, subjects performed best if both sounds were pure tones (c.f. Fig. 5). Here, the mean matching error was at about a quarter of an octave with a standard deviation of a quarter of an octave. By testing that the condition NBN-Sin would result in the highest matching error, in a preplanned manner we confirmed (estimation of contrast: −1.064; standard error: 0.342; $p = 0.004$), that subjects achieved lowest performance when they were asked to match sinusoidal test sounds to NBN targets. In this case matching errors became even larger than three quarter of an octave with a standard deviation of almost one octave. When an NBN had to be matched to either an NBN or a sinusoidal target sound subjects' performance did not differ showing matching errors of a half of an octave ± ¾ octave (mean ± SD).

For the sake of completeness, the significance (uncorrected p-values) of the pairwise multiple comparisons for all 4 conditions are shown in Table 3.

In a follow-up analysis we further investigated how far the pitch matching error depended on the target center frequency. A one-factorial ANOVA with four levels representing the different target center frequencies demonstrated that the pitch matching performance depended on the pitch of the target ($F_{(3, 87)} = 3.366$; $p = 0.021$). In multiple-comparison tests applied to the outcome data of the ANOVA the matching errors differed significantly ($p = 0.015$, Bonferroni corrected) for target center frequencies of 4000 and 8000 Hz. The participants reached highest accuracy for 4 kHz. All other comparisons did not reach significance. The results on group pitch matching performance as a function of target center

Table 3
(Experiment 2) Significance levels (p-values) derived from pairwise comparisons of pitch matching conditions.

Condition (target - test sound)	Sin - NBN	Sin - Sin	NBN - Sin
NBN - NBN	0.479	0.050	0.270
Sin - NBN		0.103	0.032
Sin - Sin			0.003

All given p-values are uncorrected.

frequency are shown in Table 4.

Fig. 6 illustrates the group performance when subjects in an additional step matched the bandwidth of the NBN sounds after they performed the pitch matching for the condition NBN-NBN. The difference in bandwidth between target and test sound across subjects was 0.035 ± 0.075 octaves (median ± SD). Only two out of thirty participants over-estimated the bandwidth of the target (resulting in negative values for the difference shown in Fig. 6). Just in three out of 30 matches the test subjects made an error larger than 1/8 of an octave when adapting the NBN bandwidth.

In both experiments and over all conditions the subjects were able to match the pitch of the target and test sounds with an error of 0.405 ± 0.652 octaves (mean ± SD). In approximately 10% of the tests, the subjects showed matching errors above one octave even after performing an octave confusion test. This was not restricted to some individuals or specific testing conditions, but it was distributed across the whole subject group.

4.3. Experiment 1 and 2 (follow-up)

The outcome of one-sample t-tests applied post-hoc to the original signed values of the difference between target and test sound frequencies for all conditions of each of the two experiments is shown in Tables 5 and 6.

Target sound: NBN with fixed bandwidth of 1/32 octave, center frequency: 4000, 6350, 8000 or 10079 Hz; matching errors represent the difference of target minus test sound center frequency; matching errors derived for different target center frequencies are accumulated; positive matching error values represent an under-estimation of target frequency, negative an over-estimation; the minimal (absolute) matching error subjects could reach and NOT representing a *perfect match* was 1/12 octave; p- and t-values derived from one-sample t-tests (hypothesis: mean equal to zero) values for mean and standard deviation are expressed in octaves.

In Experiment 1 the participants significantly under-estimated the target frequency (Table 5: positive mean values, $p < 0.001$ for hypothesis mean equal to zero) for all conditions (NBN bandwidth).

In experiment 2 the participants only underestimated the target frequency when they were asked to match a sinusoidal test sound to an NBN target (Table 6: condition NBN-Sin). In general, for both experiments, the majority of subjects underestimated the target frequency (Tables 5 and 6: last row).

5. Discussion

The goal of this study was to investigate pitch matching performance in a group of control subjects not suffering from tinnitus. More specifically, we aimed to evaluate how adequate narrow band noise sounds can be applied as test stimuli in such a scenario. Assuming, that even a tonal tinnitus percept contains some spectral content, the outcome of this study is meant to be translated to improved approaches for tinnitus frequency determination.

Table 4
(Experiment 2) Subject Group pitch matching performance expressed as absolute difference between center frequencies matching two sounds as a function of target sound center frequency.

Target Sound Center Frequency [Hz]	4000	6350	8000	10079
Group Mean	0.268	0.464	0.786	0.583
Standard Deviation	0.359	0.445	0.923	0.753

Target sound: sinusoidal or NBN with fixed bandwidth of 1/32 octave, matching errors derived for different test sound bandwidths are accumulated; matching errors represent the difference of target minus test sound center frequency all values are expressed in octaves.

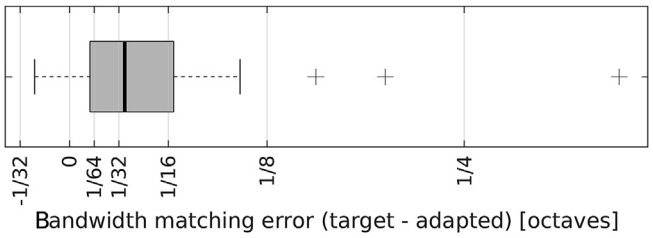

Fig. 6. (Experiment 2) Subjects' group performance adapting bandwidth of target and test NBN sounds; in each box median value (centered thick line), lower and upper quantile, whisker, and outliers (crosses) of the matching error are shown.

Table 5
(Experiment 1) Pitch matching performance expressed as signed difference between center frequencies matching two sounds having different bandwidths.

Test Sound Bandwidth	1/8	1/16	1/32	1/64
Group Mean	0.344	0.407	0.425	0.486
Standard Deviation	0.65	0.743	0.674	0.75
t-value	4.1	4.24	4.88	5.02
p-value (Bonferroni corrected)	< 0.001	< 0.001	< 0.001	< 0.001
Number of Subjects (out of 60) who over-estimated or under-estimated target frequency	11 39	7 36	5 41	7 41

Table 6
(Experiment 2) Pitch matching performance expressed as signed difference between center frequencies matching two sounds having different signal type.

Matching Condition (target − test)	NBN-NBN	Sin-Sin	NBN-Sin	Sin-NBN
Group Mean	0.364	0.122	0.558	0.158
Standard Deviation	0.863	0.38	0.989	0.736
t-value	2.31	1.76	3.09	1.18
p-value (Bonferroni corrected)	0.112	0.357	0.017	0.994
Number of Subjects (out of 30) who over-estimated or under-estimated target frequency	9 18	10 15	9 18	13 13

Matching errors represent the difference of target minus test sound center frequency; positive matching error values represent an under-estimation of target frequency, negative an over-estimation; the minimal (absolute) matching error subjects could reach and NOT representing a perfect match was 1/12 octave; p- and t-values derived from one-sample t-tests (hypothesis: mean equal to zero) values for mean and standard deviation are expressed in octaves.

A group of 30 healthy subjects performed a pitch matching test battery over two sessions, supported by a fully automated computer-based procedure. Each subject was able to complete the task matching target and test sounds, one or both being either a pure tone or an NBN.

We were able to show that the choice of the test sound signals type matters for the pitch matching performance. Though subjects performed best when they were asked to match two sinusoidal sounds, the pitch matching error was highest for a sinusoidal test and an NBN target sound. In general, using an NBN as the test sound participants performed similarly regardless of target type. On the other hand, the results considerably differed depending on targets' signal type when using a sinusoidal test sound. The frequency matching errors determined for an NBN test sound were in between those of a sinusoidal test signal. In summary, if the target sound cannot be described with certainty as a sinusoidal signal, a pure tone represents the worst choice of a test sound being used in pitch matching tests. Since on the other hand subjects' performance deteriorated only slightly when matching an NBN sound to either a sinusoidal or an NBN sound compared to matching two

sinusoidal sounds, as main outcome of this study, we suggest to use an NBN as test sound if the signal type of the target is not *a priori* known.

Overall, on average across subjects and conditions the pitch matching resulted in frequency errors of about half of an octave. However, there were also subjects demonstrating relatively large individual differences in their performance, reaching matching errors of more than two octaves.

Compared to the outcome of other studies that investigated frequency discrimination (Moore, 1973; Wier et al., 1977) and pitch matching (Markides, 1981) on normal hearing participants, the matching errors determined with our approach were much larger. In the study of Moore, the subjects were able to distinguish between two consecutively presented narrow band noise sounds if their center frequencies differed by at least 1/100 octave at a target center frequency of 4 kHz and 1/35 octave at a target center frequency of 6 kHz. This behavior depended on the bandwidth of the noise. The values mentioned above are those for poorest performance at a bandwidth of 1/22 octave. The participants in our study performed weaker when matching two NBNs. For a target center frequency of 4 kHz the matching error resulted in 1/7 octave, for a target frequency of 6 kHz it was at 2/5 octave. To the best of our knowledge so far, the discrimination for narrow band noise sounds has not been investigated in a group of normal hearing subjects based on a pitch matching approach. Hence, we decided to compare our results obtained for matching two NBNs with those derived in the study of Moore.

The studies of Wier et al. (1977) and Markides (1981), mentioned above, investigated the frequency discrimination in respect to pitch matching abilities for sinusoidal sounds. Compared to the results obtained by Moore (1973), they could show that normal hearing participants perform better discriminating sinusoidal compared to band noise sounds. This is totally in line with our finding that the error matching two NBNs is slightly higher than matching two pure tones. In the study of Wier et al. (1977) the participants reached a frequency discrimination limen of 1/125 octave for a frequency of 4 kHz and 1/75 octave for 8 kHz. More relevant to our approach, Markides (1981) found errors of 1/30 octave when the participants had to match the pitch of two sinusoidal tones at a target frequency of 4 kHz. This pitch matching performance was a lot weaker than the frequency discrimination limens reported in the studies mentioned before. In our evaluations we determined pitch matching errors of 1/9 octave at a frequency of 4 kHz and 2/5 octave at a frequency of 8 kHz for sinusoidal target and test sounds. We see several reasons for the discrepancy between the matching performance evaluated in previous studies and the results that derived from our approach.

First of all, the participants of the previous studies passed a training in which they got familiar with the procedure and the task. We omitted this preparatory part, since in a clinical application having a patient performing the pitch matching, typically the investigation time is limited. Furthermore, the course of actions implemented in the different testing procedures has an impact on the matching performance. We used the repetitive two-alternative forced choice testing. In the studies of Moore (1973) and Wier et al. (1977) participants were asked to judge on the frequency of two consecutively presented tones. Markides (1981) used an approach where the subjects could freely adjust the frequency of a test sound based on a target tone. Moreover, in all three previous studies the procedure started at an initial test sound frequency close to the target frequency. We did not want to follow a similar approach in order for our procedure to be applicable in the same way when performed by patients suffering from tinnitus without knowing the frequency of the percept in advance.

In the study of *Moore* the sounds were presented with an intensity of 40 dB SL, which is 20 dB higher compared to our study. Frequency discrimination respectively pitch detection can be affected by signal loudness (Davis and Silverman, 1961).

For the reasons mentioned above the participants of our study did not perform as good in matching sinusoidal or NBN sounds as shown in previous studies. Nevertheless, we still consider our main finding, an NBN being the more appropriate test sound in a pitch matching, as valid, since in our opinion a generally weaker performance should not have a specifically different impact on one of test conditions applied here (Sin-Sin, Sin-NBN, NBN-Sin and NBN-NBN), even though we cannot support this predication with data.

Even though our main focus was on the absolute frequency matching errors, we further evaluated the data based on the signed error values in order to judge whether subjects chronically under- or over-estimated the pitch. On the whole, the majority of the participants tended to under-estimate the target frequency. Nevertheless, when comparing the signed values of the matching errors for the different pairs of target and test sounds in experiment 2, the effect was significant, only when they were asked to match a sinusoidal test sound to an NBN target. This finding supports the main outcome of this study that a pure tone represents the worst choice of a test sound being used in pitch matching tests, which we already obtained from the analysis based on the absolute values of the matching errors.

Along with the frequency matching performance evaluation, we also investigated participants' ability matching the NBN bandwidth. For this purpose, in the final step of experiment 2, we asked subjects to adapt the bandwidths of two NBNs. Thereby, we derived the initial centre frequencies of target and test sound from the preceding pitch matching. In general, subjects tended to slightly over-estimate the bandwidth of the target sound. Interestingly, the median difference in bandwidth almost corresponded to the effective difference between bandwidth of test (1/16 of an octave) and target (1/32 of an octave) sound. That means, that even though the participants could have *corrected* for the difference in bandwidth of test and target sound, they did not. This is in line with our findings in experiment 1, where subjects showed the best performance in matching two NBNs which have a bandwidth difference of 1/32 octave. Since to our best knowledge the discrimination of NBN bandwidth has not been investigated so far, we cannot compare these results with previous findings. It might be valuable to further, systematically, investigate the threshold for equality discrimination in the bandwidth of two NBNs. In contrast to the approach followed in the present study, one should ensure both sounds having the same center frequency. The outcome might have an impact on knowledge regarding the accuracy with which one can conclude on the spectral content of a tinnitus percept, when this information is derived from a pitch matching based on NBN test sounds.

Since, as mentioned above, we could not revert to previous findings, before evaluating participants' frequency matching performance in experiment 2, we determined the proper bandwidth of the NBN test sounds in experiment 1. Thereby, subjects' performance on matching of two NBN signals did not differ significantly in relation to the test sound bandwidths. However, the best performance was achieved for a bandwidth of 1/16 octave. The testing here was performed only for target sounds having a fixed bandwidth of 1/32 octave in order to reduce the number of tests per subject. This might reflect a certain limitation of the study. For future research it might be valuable to further evaluate the matching approach proposed here using NBN targets of different bandwidth.

In order to verify, whether the task of the approach introduced here was more difficult and less accurate for higher frequencies, we looked at systematic errors in pitch matching as a function of target

center frequency. This was performed as the perceptual judgment on the actual tinnitus frequency might be affected in patients who suffer from higher-frequency tinnitus (e.g. above 8 kHz). In general, for both experiments, subjects' performance was best when matching sounds having lower center frequencies (e.g. 4 kHz). As we know, the sensitivity of the human hearing system is highest in the frequency range for speech (i.e. between 200 Hz and 6 kHz), and this might be the reason which caused this effect. Even though in experiment 1 participants' performance was significantly worse for all other target center frequencies (6 kHz, 8 kHz and 10 kHz), in experiment 2 the matching errors only differed for 4 and 8 kHz. Thus, subjects did not perform generally better for lower target frequencies. In our opinion, the relatively low number of samples (only four different target center frequencies) and the fact that they are not equally distributed on an octave scale, does not justify, to draw conclusions on the pitch matching performance as a function of target frequency.

We conducted this study as an initial evaluation on control subjects not suffering from tinnitus. Nevertheless, we intended to contribute with the outcome of this study to the methods of pitch determination applied on tinnitus patients. We simulated the tinnitus percept by presenting an external stimulus to the subjects. Thus, knowing the real target frequency, enabled us to evaluate the general pitch matching performance. The present study differs from other studies, in which various approaches for a better determination of the pitch and specifically the spectral contents of the tinnitus percept have been investigated on patients (Henry et al., 2013; Norena et al., 2002; Roberts et al., 2008). For further evaluation, the method presented here and the "frequency likeness-rating" approach introduced by Norena et al., (Norena et al., 2002) should be applied on a group of control subjects.

As a limitation of this study, the choice of the spectral shape of the NBNs might have had an impact on the performance especially when matching them with a sinusoidal sound. Choosing a rectangular shaped NBN had been an arbitrary decision. Even though presumably the internal perception resembles an NBN, there is no reason to assume that this is rectangularly shaped. Participants' performance might have been better in case the spectra peaking at a given frequency and having a rounded shape with less spectral power at the filter cut offs (inverted u-shape). To maximize performance, the spectral peak of the NBN should coincide with the frequency of a sinusoidal sound when matching them. Derived from these considerations, it is valuable for future research to evaluate the matching performance of controls or even tinnitus sufferers using NBNs having different spectral shapes.

Furthermore, participants' overall pitch matching performance when using an NBN as test or target sound might have been weakened due to random amplitude fluctuations within NBN stimuli. Since this makes it even harder to extract the center frequency, especially for sinusoidal sounds matched with an NBN, results might have been poorer. Typically, a tinnitus sensation does not present such amplitude modulations; this has to be considered when investigating the performance of patients, suffering from tinnitus, in matching their percept with an NBN.

5.1. Clinical application

A series of studies (De Ridder et al., 2011; Eggermont, 2007; Møller, 2007) demonstrated that tonal tinnitus is mainly caused by a malfunctioning of neurons in the auditory cortex. However, not a single neuron but rather a population of neighbouring neurons with similar characteristic tuning frequencies is involved in this process. Hence, the resulting tinnitus percept, in case of tonal tinnitus, should resemble an acoustic signal having a prominent center frequency and a small spectral extent. These properties are featured best by an NBN sound. In the case of tonal tinnitus, the patients often cannot reliably state, whether their percept is rather similar to a pure tone or resembles a spectrum of sounds including closer frequencies. As the main outcome of this study, considering the aforementioned, we therefore suggest to perform first a pitch matching procedure using an NBN as test sound in order to better quantify the (dominant) frequency in the cases of tonal tinnitus. In a subsequent step, the patient should further adapt the signal bandwidth in order to get a better estimation of the spectral extent. Repeating these steps for several times and using the outcome of the preceding step as input (test sound) to the consecutive one, might even improve the results. Furthermore, this method applied in combination with the "frequency likeness-rating" approach introduced by Norena et al., (Norena et al., 2002) could lead to an improvement in the assessment of both the (center) frequency and the spectral contents of a tinnitus sensation. A frequency likeness-rating performed prior to the method introduced here could provide to the investigator more specific information regarding the bandwidth which is appropriate to use for an initial set up of the NBN test sound. For patients suffering from a tonal tinnitus with pronounced center frequency, the outcome might represent a more realistic and comprehensive estimation of their tinnitus percept (Henry, 2016). Therefore, using our approach might be a valuable tool in clinical environments, when performing tinnitus pitch matchings.

Typically, in a clinical environment a single tinnitus pitch matching procedure using pure tones as test stimuli is applied. In order to improve the reliability of the frequency determination, this procedure has to be repeated several times, which results in long lasting sessions (up to an hour). However, patients' responses can typically vary over 2-3 octaves (Burns, 1984; Tyler and Conrad-Armes, 1983). When applying our approach on control subjects the mean matching errors across all conditions were below 1 octave including some few subjects showing errors above 2 octaves. In addition, a single pitch matching based on the recursive two-alternative forced-choice test including the loudness adaptation and the octave confusion test did not last longer than 10 min. This time improvement is very important and advantageous within clinical environment.

Assessing the tinnitus pitch in subjects with hearing loss might lead to a potential problem that is common for all pitch matching methods including the one introduced here. Assuming that the dominant tinnitus pitch is usually located in the frequency range of hearing loss, any stimulus in this frequency band may be perceived as distorted, in particular in presence of dead regions (Huss and Moore, 2005; Moore and Vinay, 2010). One has to take that into account, when the approach introduced here will be applied in a clinical setting.

6. Conclusion

The goal of this study was to evaluate whether an NBN compared to a sinusoidal sound is the more valuable test stimulus being used in pitch matching procedures. We were able to demonstrate, in a group of healthy subjects, that the performance in pitch matching of two sounds strongly depends on the proper choice of the spectral characteristic of the signals to be compared. Subjects performed best when matching two sinusoidal sounds. Using a sinusoidal test sound to match an NBN target with regard to the matching error was revealed as the worst choice across all four combinations of test and target sounds (Sin and NBN). Currently, the identification of tinnitus perception relies on the subjects' report and, hence, lacks objective knowledge on the exact tinnitus signal characteristic. Transferring the outcome of this study to pitch matching in tinnitus patients, could provide to researchers and

clinical investigators a tool for more reliable measures of the tinnitus pitch and its spectral contents. Beyond that, the efficiency of therapy approaches relying on further knowledge of signal characteristics will profit from this more reliable estimation.

Conflicts of interest

The authors declare no competing financial interests.

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Appendix A. Supplementary data

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