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Relationship between irregularities in SOAE suppression and psychophysical tuning curves

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ABSTRACT

The suppression of spontaneous otoacoustic emissions (SOAEs) allows the objective evaluation of cochlear frequency selectivity by determining the suppression tuning curve (STC). Interestingly, some STCs have additional side-lobes at the high frequency flank, which are thought to result from interaction between the probe tone and the cochlear standing wave corresponding to the SOAE being suppressed. Side-lobes are often in regions of other neighboring SOAEs, but can also occur in the absence of any other SOAE. The aim of this study was to compare STCs and psychoacoustic tuning curves (PTCs). Therefore, STCs and PTCs were measured in: (1) subjects in which the STC had a side-lobe, and (2) subjects without STC side-lobes. Additionally, PTCs were measured in subjects without SOAEs. Across participant groups, the quality factor $Q_{10\text{dB}}$ of the PTCs was similar, independently from whether SOAEs were present or absent. Thus, the presence of an SOAE does not provide enhanced frequency selectivity at the emission frequency. Moreover, both PTC and STC show irregularities but these are not related in a straightforward way. This suggests that different mechanisms cause these irregularities.

Keywords

Frequency selectivity, Spontaneous otoacoustic emission, Suppression tuning curves, Psychoacoustic tuning

Abbreviations

NTC: Neural tuning curve

PTC: Psychoacoustic tuning curve

SOAE: Spontaneous otoacoustic emission

SPL: Sound pressure level (re. 20 μ Pa)

STC: Suppression tuning curve

TC: tuning curve

TC-tip: Tuning curve lowest threshold

CF: Characteristic frequency

Declaration of interest

The authors declare no competing financial interests.

Contributors

S.E., E.G., P.v.D., and E.d.K. designed the study. S.E. performed the measurement and wrote the manuscript. S.E. and E.G. conducted the analysis and visualized the data. All authors contributed in writing the manuscript, verified and approved its final version.

I. INTRODUCTION

Frequency selectivity is the ability to separate a complex sound into its pure tone components (e.g., Moore, 1989). The auditory frequency selectivity of an individual can be determined through objective (e.g. suppression tuning curves, STCs) or behavioral measurements (e.g. psychophysical tuning curves, PTCs). Physical measurements of frequency selectivity (STCs) rely on recordings of physiological properties from the auditory system whereas behavioral measurements (PTCs) rely on behavioral responses from the participants. Both measures are based on interaction between signals. In one type of STCs, spontaneous otoacoustic emissions (SOAEs) are suppressed by external tones. This suppression is thought to be based on overlap between the basilar membrane (BM) excitation patterns of the SOAE and that of the suppressive tone. In simultaneous PTCs, the perception of a target tone interferes with the presentation of a masker, for example a narrow band noise. The perception of the target tone can be hindered when the BM excitation pattern of the tone overlaps with that of the masker. For STCs, frequency selectivity is determined by measuring the level of the suppression tone that yields a certain level of SOAE suppression, for different frequencies of the tone. Similarly, for PTCs, frequency selectivity is determined by measuring the masker level that corresponds to the detection threshold of the target tone, as a function of the masker frequency. The tuning curves (TCs) are essentially V-shaped, where the tip of the tuning curve, the most sensitive point, is close to the SOAE in STCs, or the target tone in PTCs.

Although the methods used to obtain STCs and PTCs have a lot in common, the two measures reflect very different processes. While PTCs require the listener to solve an auditory scene analysis problem and make a decision about the presence or absence of a tone embedded in noise, thus involving the whole peripheral and cortical auditory system, STCs are limited to the most peripheral

level. Understanding the differences between the two measures can thus potentially reveal how frequency selectivity evolves from the periphery to more central brain areas (Langers and van Dijk, 2012; Moerel et al., 2012). Further, comparing PTCs — who can be measured in virtually any normal-hearing listener — to STCs — who can only be measured in listeners with SOAEs — offers the opportunity to better understand the mechanisms underpinning the presence of SOAEs, and what effect they may have on perception.

When comparing frequency tuning measured with SOAE-STCs and simultaneous masking PTCs, both measures are in good alignment across individuals (Zizz and Glattke, 1988). Still, it was suggested that the presence of SOAEs influences the appearance of PTCs. According to the literature, spontaneously emitting ears appear to have sharper PTCs when using simultaneous, tonal maskers, at least at, or close to, the SOAE frequency (Bright, 1985; Micheyl and Collet, 1994). It was suggested that PTCs in which the target tone was centered to an SOAE were more sharply tuned compared to ears without SOAEs (Bright, 1985). Baiduc and colleagues (2014) also investigated the relation between PTC sharpness in ears with and without SOAEs. However, they used narrowband noise maskers rather than tones, and found no difference in frequency tuning at emission frequency. The interaction between a tonal masker and an SOAE can be perceived by the participant as beating (Wilson, 1980; Long and Tubis, 1988a), which could explain the sharper PTCs observed at emission frequency by Bright (1985). To avoid the generation of such perceptual cues, we chose a simultaneous noise masker instead.

Because TCs are generally V-shaped and reflect selectivity, they are primarily characterized by their sharpness. However, some TCs show irregularities, causing them to deviate from the typical V-shape. In SOAE-STCs, additional suppression side-lobes were observed, characteristically at about

0.5 and 1 octave above the SOAE frequency (Manley and van Dijk, 2016; Engler et al., 2020). It has been suggested that these side-lobes reflect interactions between a BM standing wave corresponding to the emission frequency and the presented tone (Manley and van Dijk, 2016). Alternatively, interactions between multiple SOAEs in the same ear could result in irregular STCs. PTCs can also deviate from the V-shape, with peaks and dips at frequencies away from the probe-tone frequency (Baiduc et al., 2014). These irregularly shaped PTCs appear to be more common in ears with SOAEs (Baiduc et al., 2014), suggesting that the presence of SOAEs could influence the perception of target tones. In PTCs the masker could produce similar dips, as seen in SOAE-STCs produced by the presented tone.

The objective of the present study is to compare STCs to PTCs, both in their sharpness and in the presence or absence of irregularities in their shape. Since the irregularities of both the STCs and PTCs have been attributed to similar cochlear mechanisms, we hypothesized that PTCs measured with a target tone placed at an SOAE frequency would yield TC irregularities that are related to side-lobes in the STC of that emission. Conversely, if the STC does not show side-lobes, the corresponding PTC would be expected to be simply V-shaped. To verify this, STCs and PTCs were measured in participants with SOAEs. Both types of STCs, namely with and without side-lobes were included. Additionally, PTCs were also obtained from listeners without detectable SOAEs. In absence of SOAEs, no irregularities in the PTCs are expected.

The aim of this study was to directly compare the frequency selectivity and the shape of SOAE-STCs to PTCs from the same ear, tested at the SOAE frequency. We investigated whether the additional side-lobes in STCs are reflected in the shape of PTCs and whether PTC side-lobes are absent in people without SOAEs.

II. Material and Methods

A. Participants

Prospective participants were screened, in both ears, for the presence of SOAEs and for normal hearing. Only ears that showed clear SOAE peaks of at least 3 dB above the microphonic noise, or ears without any recordable SOAE peaks were chosen. After screening, 26 participants were included. One ear per participant was included in the measurement. The chosen ear was then categorized in one group with SOAEs (n=17) and one group without SOAEs (No SOAE group, n=9). The group with SOAEs was subdivided depending on whether STC side-lobes were present (SL group, n=8) or absent (NSL group, n=9). A high frequency STC side-lobe was defined as the reduction in STC slope in relation to the expected high frequency slope, followed by a relatively abrupt increase in slope again. Thus, side-lobes were visible as secondary dips in the STC. The number of SOAEs per tested ear did not differ significantly (Mann-Whitney U=43.5, p=0.48) between the SL and NSL group. However, participants with eight or more SOAEs were observed in the SL group only.

Participants self-reported no history of ear pathologies. All participants had normal hearing with pure tone thresholds ≤ 25 dB hearing level at octave frequencies between 0.25 and 8 kHz (Audiosmart, Echodia, Clermont-Ferrand, France). The median age of all tested adults (n=26) was 29 years (ranging from 22 to 48 years). In total, 11 participants had some degree of musical training. With the highest level of musical training, seven of these can be seen as non-professional musicians. None of the included participants had been playing an instrument for more than 10 years nor was practicing music daily (definition of professional musicians: Micheyl et al., 2006). All participants were naive to the test-routine. Nine subjects participated in forced choice experiments before, but

none in a similar masking study with simultaneous noise and a three-alternative forced choice routine.

The majority of the included participants with SOAEs were female (82.4%). Participants with STC side-lobes were exclusively female (n=8), whereas STCs without side-lobes (n=9) were also recorded in males (33.3%). In the participant group without SOAEs, the sex representation was more balanced, with slightly more males than females (55.6%).

Participants provided informed consent and received monetary compensation for their participation. Both experiments were approved by the Central Ethics Review Committee of the University Medical Center Groningen.

B. Measurements

All measurements were carried out in a soundproof anechoic room of the ENT department within the University Medical Centre Groningen (UMCG, Groningen, Netherlands).

1. *SOAE recordings*

To record the SOAEs, an occluding soft foam ear plug, which included the Etymotic ER-10B microphone-speaker system (Etymotic Research, Inc., Elk Grove Village, IL, USA), was placed in the participants external ear canal. For the STC recording, an amplification of the microphone output of 60 dB was applied, by adding the 40 dB gain of the Etymotic ER-10B system and a 20 dB gain by the Stanford Research Systems amplifier (SRS Inc, model SR 640, CA, USA). The microphone signal was monitored using a spectrum analyzer (SRS Inc., model SR 760). A Motu 624 soundcard (MOTU Inc., MA, USA) was used to record the microphone signal and to generate the

tone stimuli. The playback of stimuli and recording of SOAEs was controlled by custom routines developed in Matlab (MathWorks Inc., 2016a, Natick, MA, USA) using a 24-bit resolution and a 48 kHz sampling rate.

A Lorentzian function was fitted to emission recordings with the best signal to noise ratio to estimate the SOAE characteristics, such as emission frequency (f_{SOAE}), width, and amplitude.

2. *STC measurements*

The STCs were obtained following a procedure adapted from that described by Engler et al. (2020). The procedure assesses the suppression of SOAEs by a range of subsequent stimulus tones. Stimulus tones were generated using a ER-2 driver connected to the ER-10B microphone. In an automated procedure that lasted approximately 1 h, 1.2-s probe tones, with 10-ms raised-cosine ramps, were presented ranging over 70 frequencies (0.5-9.9 kHz, in 1/16-octave steps) and 24 levels (0-70 dB SPL, in 3-dB steps), in quasi-random order. Tone levels were calibrated in-situ for each participant, with the emission probe placed in the ear canal, and using the emission microphone for calibration. For each presented stimulus, the SOAE level was computed. A tonal signal with a frequency equal to the stimulus (f) plus two higher harmonics ($2f$, $3f$) was fitted to the recorded signal by a least squares minimization procedure. The fitted stimulus was then subtracted from the recorded signal to include the SOAE but not the presented stimulus. SOAEs were filtered by a narrow FFT bandpass filter to estimate the SOAE peak frequency. For details of the STC analysis the reader is referred to Engler et al. (2020). The reference magnitude of the emission was estimated using the Hilbert transform, as the mean of the module of the analytic signal expressed in decibels.

The suppression was calculated as the difference between the measured emission level at a given probe tone level and frequency and the reference emission level.

The STC was calculated by estimating the -3 dB iso-contour using Matlab's contour function (Fig. 1). Multiple contours can be returned, as local noise in the recordings can cause accidental closed contours to arise in areas remote from the STC. The obtained contours were thus curated with an automatic routine to keep only the contour depicting the STC.

3. *PTC measurements*

The PTCs were measured by estimating the masking threshold of a target tone by narrow bands of noise centered on different probe frequencies covering the expected shape of the tuning curve. Because potential side-lobes were expected to fall within 0.5 to 1 octave above the PTC-tip, as seen in STCs (Manley and van Dijk, 2016; Engler et al., 2020), the probe frequencies ranged from -0.9 to +1.4 octaves relative to the tone frequency, by steps of 0.1 octave.

For each probe frequency, the threshold was obtained using an adaptive (2-down, 1-up) three-interval, three-alternative forced choice (3I-3AFC) method. Two of the intervals were the masker alone, while the odd-one-out, that the participants were instructed to detect, contained the target tone and the masker. Participants were shown an interactive interface that displayed three buttons on a computer screen. Each button lightened up when an interval was presented. The participant then had to choose the button corresponding to the odd-one-out, and was given visual feedback after responding.

When two correct responses were given in a row, the level of the masker was increased by the step size, and for every incorrect response, the level was decreased by the step size. The step size started at 5 dB, but was decreased to 2 dB after the first reversal. The procedure continued until 8

reversals were observed; the masking threshold was calculated as the average of the masker level over the last 6 reversals.

The target tone was centered on the emission frequency of interest, and lasted 200 ms with 20-ms raised cosine ramps. The masker had a duration of 300 ms, with 20-ms raised cosine ramps, and consisted of a band of noise of $\frac{1}{3}$ octave width (slope 288 dB/octave) centered on the probe frequency. When the target and masker were added together, the target was temporally centered in the masker. The intervals were separated by a silence of 300 ms. The target level was set to 10 dB sensation level, after the absolute threshold was measured. The initial masker level was adapted to the probe frequency, following the general shape of PTCs reported in the literature (adjusted from Moore, 1978) in order to reduce unnecessary trials and arrive close to the threshold.

When hovering close to the detection threshold for too long, the target tone detection gradually became very difficult. To help the participant, a ‘target reminder’ was presented after four consecutive incorrect responses, as well as at the beginning of each adaptive track, i.e. every time a new masker frequency started. Participants did not need to respond to this target reminder.

During the PTC measurement, the same equipment with the same settings was used as for the STC measurements. Except for two participants, the masking-noise output was presented through the headphone driver (HB 7 Headphone Buffer, Tucker-Davis Technologies).

C. Procedure

The STC and PTC recording procedures encompassed three main steps: (1) Two-minutes of SOAE recording without any external stimuli. For participants with SOAEs, this step was followed by (2a) the STC measurement (~60 min). Further, for all participants, (2b) the PTC were then

measured (~60 min). Finally, (3) a two-minute SOAE recording, equivalent to step 1 was repeated to ensure SOAEs had not changed.

The STC data was (except for one participant) collected prior to the PTC measurement. For the majority of participants, the STC measurements were taken from an earlier experiment, thus the data is partly included in the publication of Engler et al. (2020). In all cases, steps 1 and 3 were performed twice (for both sessions). Comparing the SOAEs recorded on both measurement days, they were in good agreement with each other. Median differences between STC and PTC measurement day were 1.59 Hz (sd: 9.09 Hz) for SOAE frequencies and 0.36 dB (sd: 4.47 dB) for the SOAE levels.

For participants with SOAEs, the PTCs were measured at the selected SOAE frequency. For the participants that did not have SOAEs (No SOAE group), the PTCs were measured at a frequency that matched that of a participant with SOAE. Details of the participant grouping is provided in Supplementary Table I (See supplementary material at [URL will be inserted by AIP]).

To make sure that the three-alternative forced choice task was well understood from the beginning of the PTC measurement, all participants received the same training prior to the actual measurement. During the training, the frequency of the target tone was always set to 2.5 kHz. The absolute threshold determination of the target tone was followed by a shortened procedure where only masker frequencies at 2.18 and 2.87 kHz were tested.

D. Data analysis

For both STC and PTC, the tip was defined as the lowest point in the vicinity of the target frequency. The frequency selectivity can be quantified as the filter quality factor $Q_{10\text{dB}}$ of the TC. This

factor is defined as the ratio between the tip-frequency and the width of the TC at 10 dB above its tip, using linear interpolation if necessary.

Another way of characterizing sharpness is to estimate the slope of the TC for each flank. This has the potential of revealing the asymmetries in TC shapes, whereas the $Q_{10\text{dB}}$ only concerns the width. The slopes of the low and high-frequency flank were estimated as the average slope, obtained by linear interpolation, on a segment of the TC between the tip and 25 dB above it. The average tuning curves were calculated with a generalized additive model (GAM) based on likelihood-based fits, presenting confidence intervals of 95%.

Statistical analyses were performed in IBM SPSS Statistics (Version 23) and Matlab. Because of the small sample size, we could not guarantee that the data represents a normal distribution, therefore we chose a non-parametric test. The Kruskal-Wallis test was used for comparisons across tested groups, reporting the H statistic. For pairwise comparisons between STC and PTC recordings within and across the tested groups of participants the Mann-Whitney U test was applied, also reporting the *H*-statistic.

Smooth average estimates of the TCs for each group were obtained in R (v4.0.3, R Foundation for Statistical Computing, Vienna, Austria) using a generalized additive model (mgcv, v1.8-33, Wood, 2011) as implemented in ggplot2 (v3.3.3, Wickham, 2016).

III. Results

Data extracted from the TCs to compare them were: TC tip level and tip frequency, the high and low TC slopes, and the $Q_{10\text{dB}}$. Overall STCs and PTCs showed the typical V-shape, with asymmetric flanks. TC tips were near the SOAE frequency in STCs or the target tone in PTCs. A selection of representative TCs is displayed in figure 1. Note that STC side-lobes may occur in absence (Fig. 1A)

or presence (Fig. 1B and C) of other neighboring SOAEs. Corresponding PTCs may also show irregularities in tuning curve shape (Fig. 1A and B), but may also be smoothly V-shaped (Fig. 1C). PTCs may have side-lobe-like irregularities in absence of STC side-lobes or neighboring SOAEs (Fig. 1D), as well as in presence of neighboring SOAEs (Fig. 1B). Irregular and smoothly shaped PTCs occur also in participants without SOAEs (Fig. 1F and G).

Insert Figure 1 around here

Figure 2 shows all individual tuning curves, as well as the averaged tuning curves per subject group. STCs of the SL group showed a clear difference at the high frequency flank compared to the NSL group (Fig. 2A). The STCs of the SL and the NSL group deviate significantly (no overlap of the 95% confidence intervals) around 0.5 oct. above SOAE frequency, the region of primary side-lobes. The PTCs of the three groups did not differ significantly from each other (Fig. 2B). In general, STCs appeared to be more sharply tuned than PTCs (Fig. 2C).

Insert Figure 2 around here

STC tip levels did not differ significantly ($H(1)=0.59$, $p=0.44$, $\eta_H^2=0$) between the SL (17.22 dB SPL) and the NSL group (14.37 dB SPL). The median PTC tip levels were also similar between all three groups (SL-group: 17.13 dB SPL; NSL-group: 16.33 dB SPL, and No SOAE group: 15.58 dB

SPL; $H(2)=0.81$, $p=0.67$, $\eta_H^2=0$). Thus, TC tip levels were similar between STC and PTC measurements and between participant groups.

For all tuning curves, the quality factor $Q_{10\text{dB}}$ was evaluated as a measure of the frequency selectivity (Fig. 3A, Table I). STCs of participants with SL were similarly sharply tuned compared to the NSL group (median $Q_{10\text{dB}}$: 4.25 and 5.51, respectively; $H(1)=1.81$, $p=0.18$, $\eta_H^2=0.05$). Also, the frequency selectivity of the PTCs was similar in all three groups. PTCs of the SL group (median $Q_{10\text{dB}}$: 3.48) were similar compared to the NSL group (median $Q_{10\text{dB}}$: 2.72; $H(1)=1.12$, $p=0.29$, $\eta_H^2=0.01$) and the No SOAE group with participants without SOAEs (median $Q_{10\text{dB}}$: 2.99; $H(1)=1.56$, $p=0.21$, $\eta_H^2=0.04$). Therefore, the NSL group and the No SOAE group had also no significant differences in PTC sharpness ($H(1)=0.33$, $p=0.57$, $\eta_H^2=0$).

Secondly, to answer the question to what extent cochlear tuning may differ from psychoacoustic tuning we compared $Q_{10\text{dB}}$ within each group and between the two methods (STC-PTC comparison; Fig. 3A). In the SL group, the $Q_{10\text{dB}}$ of STCs and PTCs were not significantly different from each other ($H(1)=2.48$, $p=0.12$, $\eta_H^2=0.25$). However, in this same group, STCs had significantly steeper low ($H(1)=5.34$, $p=0.021$, $\eta_H^2=0.31$) and high ($H(1)=4.41$, $p=0.036$, $\eta_H^2=0.24$) flanks, compared to the low and high flanks of the PTCs (Fig. 3B).

The NSL group had significantly sharper STCs than PTCs ($H(1)=10.39$, $p=0.001$, $\eta_H^2=0.11$). Also, for the NSL group, low and high flanks of the STC were significantly steeper compared to the

PTC flanks ($H(1)=5.9$, $p=0.015$, $\eta_H^2=0.31$ and $H(1)=5.07$, $p=0.024$, $\eta_H^2=0.24$; respectively). Details can be seen in table I.

TABLE I. Comparison of STC and PTC measurements across groups. Shown are the median quality factors and slopes of the tuning curves, per group (Fig. 3).

Group measurement	Median Q_{10dB}	Median slope low (dB/oct.)	Median slope high (dB/oct.)
SL			
STC	4.25 (sd: 1.39)	-72.42 (sd: 64.75)	73.87 (sd: 16.50)
PTC	3.48 (sd: 1.18)	-49.99 (sd: 19.41)	46.89 (sd: 11.92)
NSL			
STC	5.51 (sd: 1.43)	-88.93 (sd: 38.96)	91.34 (sd: 15.15)
PTC	2.72 (sd: 0.7)	-59.28 (sd: 22.70)	53.84 (sd: 137.35)
No SOAE			
PTC	2.99 (sd:0.4)	-66.86 (sd: 20.62)	49.48 (sd: 9.27)

Insert Figure 3 around here

IV. Discussion

While PTCs indicate the limits of the auditory system in resolving two different stimuli (Moore, 1995), probing SOAE-STCs measures the suppressive effect of external tones on a spontaneous emission. STCs require overlap, on the basilar membrane (BM), of the vibration patterns corresponding to the SOAE and to the suppressor. Similarly, PTCs are based on interactions between the probe tone and the masker, which also includes interaction on the BM, but may be additionally influenced by the interactions in the central auditory system.

We investigated whether side-lobes that can be found in SOAE-STCs are also present in PTCs. Both STCs and PTCs showed deviation from the standard V-shape. We will refer to side-lobes in the case of STC, and irregularities for PTCs. This terminology seems appropriate as in STC the side-lobes are often very pronounced, whereas for PTC the irregularities may be less distinct. Some STCs show side-lobes, which are additional suppression dips. Primary STC side-lobes appear approximately at 0.5 oct. above the SOAE frequency, while secondary side-lobes can be found at about +1 oct. (Manley and van Dijk, 2016). In the current study the comparability between objective and behavioral measures of frequency selectivity was evaluated, with a focus on these irregularities (side-lobes) observed in STCs. We expected to observe PTC irregularities corresponding to the STC side-lobes. To test this hypothesis, we measured PTCs with probe tones at SOAE frequency.

A. Possible mechanisms of side-lobe generation

SOAEs are believed to correspond to standing waves in the cochlea (Kemp, 1980; Shera, 2003). When forward and backward traveling waves meet in phase, they reinforce each other and form a standing wave. Presumably, a standing wave is present between the base of the cochlea and the

characteristic place of an SOAE frequency. SOAEs are formed when frequency specific roundtrip travel requirements within the cochlea are fulfilled. A model of SOAE generation shows that the standing waves corresponding to an SOAE, have antinodes at cochlear locations with characteristic frequencies at 0.5 and 1.0 octave above the SOAE frequency (Epp et al., 2015). Interestingly, the side lobes in STCs are also about 0.5 and 1.0 above the SOAE frequency. This suggests that SOAE-STC side-lobes may be the result of the interaction between the suppressor tone with the standing wave antinode (Manley and van Dijk, 2016).

When the probe tone in the PTC measurements is placed at an SOAE frequency, it presumably generates a standing wave in the cochlea, since the frequency meets the roundtrip travel requirements that have to be fulfilled to form the SOAE. We expected that a masker in the PTC measurements would also perturb this standing wave, and thereby result in side-lobes in the PTC. Although PTC irregularities corresponded to STC side-lobes in some cases (e.g. Fig. 1A), this was not always the case (e.g. Fig. 1C). Moreover, side-lobe-like irregularities in the PTCs were also present in STCs without side-lobes (e.g. Fig. 1D) and even in absence of detectable SOAEs (Fig. 1F). Thus, all three groups showed irregularities in the shape of their PTCs, and PTC irregularities were not systematically related to STC side-lobes. In other words, the relation between SOAE suppression side-lobes and PTC irregularities is not straightforward, suggesting that they may not be generated by the same mechanism.

Some STC measurements indicate that side-lobes may occur in the vicinity of other SOAEs (Fig. 1A). Possibly, additional sensitivity dips may be caused by interactions between the probe tone and another SOAE. Moreover, SOAEs can internally interact with each other which can be very diverse and complex. For example, Murphy et al. (1995) describe the suppressive effect one SOAE can have

on another one. If the suppressive SOAE is itself suppressed by an external tone, the other SOAE is released from internal suppression. Additionally, when two SOAEs interact (primary SOAEs), distortion product SOAEs (DP-SOAEs) can be generated. Suppressing such a primary SOAE, consequently affects the DP-SOAE, leading to a reduced amplitude (e.g.: Burns et al., 1984; Jones et al., 1986; Norrix and Glatke, 1996). In other words, when suppressing a neighboring primary SOAE, the targeted DP-SOAE shows an amplitude decrease as well. Hypothetically, such internal interactions may appear as suppression side-lobes in STCs.

The presence of SOAEs does not only affect the shape of STCs. In fact, previous research has shown that SOAEs can influence the shape of PTCs (Bright, 1985; Micheyl and Collet, 1994; Baiduc et al., 2014). It was suggested that the presence of the emission might be responsible for additional suppression dips (Bright, 1985; Baiduc et al., 2014). Still, it was also shown that in two ears without SOAEs the PTC deviated from the typical V-shape (Bright, 1985). Indeed, in the current study in ears without any SOAEs 55.6% of the PTCs demonstrated irregularities (example in Fig. 1F). It could be argued that any statement about the presence of SOAEs only concerns observable SOAEs. SOAEs could be present, but remain undetected in the noise floor and may still influence PTC recordings. It is very unlikely, however, that the chosen target tone or the noise masker used in a PTC measurement would have interacted with such an undetected emission frequency in several participants, coincidentally.

B. Potential effects of the PTC masker

Characteristic frequency selectivity measure as evaluated by PTCs, is influenced by the characteristics of the applied masker. Forward masking paradigms, for instance, reveal sharper tuning

compared to simultaneous masking (e.g.: Moore, 1978), as the suppressor is not present at the same time as the stimuli. Thus, the temporal presentation of the masker relative to the target stimulus influences the frequency selectivity. Furthermore, whether the masker is a pure tone or a noise band also determines the psychoacoustic tuning results. Tonal stimuli may interact with SOAEs and cause a beating percept (Wilson, 1980; Wilson and Sutton, 1981; Zurek, 1981). Such cues can be perceived by the participant and therefore affect the shape of the PTC, potentially leading to the impression of enhanced frequency selectivity. The PTC shape has been reported to be affected by placement of the tonal masker or target tone relative to the SOAE. A target tone at the SOAE frequency can suppress or synchronize the emission (e.g.: Wilson and Sutton, 1981; Zwicker and Schloth, 1984; Long and Tubis 1988b) and will therefore not lead to frequency beating. Previously, it was suggested that PTCs derived with pure tone masking are more sharply tuned in emitting ears at SOAE frequency than off the SOAE frequency (Bright, 1985). In their study, PTCs were tested with a target tone that matched the SOAE frequency and at least 1 kHz above the emission frequency.

Such kinds of interactions are unlikely to happen when presenting noise bands as maskers, as used in the current study. Because PTCs were obtained with a masker that is spectrally broader than the suppressing tone used in STCs, it was expected that side-lobes observed in PTCs would be less pronounced than for STCs. Thus, the broadness of the noise masker itself may result in broader and/or smoother PTCs, which may obscure the sharpness of PTCs, or the presence of irregularities, in participants with SOAEs. Nevertheless, PTC irregularities were observed, indicating that the width of the chosen masker was not too broad to smooth out dips in the TC.

Micheyl and Collet (1994) compared PTCs at fixed frequencies in emitting versus non-emitting ears. In SOAE emitting ears, PTCs with tonal maskers were significantly sharper at 2 kHz, but not at

1 and 4 kHz. Moreover, ears with weak evoked OAEs showed sharper tuning than ears with strong evoked OAEs. In a more recent paper, it was shown that when using a 3 kHz target tone PTCs are not significantly influenced by the presence of SOAEs in the investigated ear (McFadden et al., 2018). In that study, neither psychoacoustic tests with notched noise, nor pure tone maskers and neither simultaneous nor forward masking paradigms were significantly influenced by the presence of SOAEs. Even though McFadden et al. (2018) reported SOAEs over a wide frequency range (0.55 to 9 kHz) it is unlikely that the majority was close to the 3-kHz target tone, since SOAEs are mostly recorded between 1 and 2 kHz (Zurek, 1981; Probst et al., 1991). Thus, it is unlikely that the SOAE and the presented target tone at 3 kHz were interacting and thereby generating any perceivable cue that may enhance the performance of the participant. In the current study, there were also no systematic differences between PTCs in ears with and without SOAEs. Altogether, psychoacoustic tuning does not seem to differ between ears with or without SOAEs.

C. Comparability of SOAE-STCs and PTCs – A matter of method?

No difference in frequency selectivity (expressed by Q_{10dB}) was observed between the three participant groups, neither for the STC nor for the PTC measurements (Fig. 2). In fact, participants without recordable SOAEs showed PTCs that are as sharp as those of participants of the SL and NSL group (Fig. 3A). Comparison of the frequency selectivity within subject groups, however, showed sharper STCs than PTCs in the NSL group, whereas Q_{10dB} values for the two measures were similar in the SL group.

In addition to the differences in STC and PTC measurements mentioned above, both measurements are highly dependent on the chosen thresholds for the tuning curve. Here, we defined

the STC contour to be a SOAE suppression of 3 dB. For PTCs, we chose the threshold as defined by 70.7% correct target tone detection by the participant (as a result of the 3-AFC procedure). These thresholds are arbitrary and different choices would consequently influence the TC sharpness. We noticed that STCs are sharper tuned when the SOAE-suppression criteria were set to higher levels (comparing 2, 3, and 4 dB of SOAE suppression, data not shown). In fact, studies with evoked emissions showed the same effect. For stimulus frequency OAEs (SFOAEs) and transient evoked OAEs (TEOAEs) STCs were sharper tuned at higher suppression levels (Kemp and Chum, 1980; Zettner and Folsom, 2003; Charaziak et al., 2013). When choosing a higher suppression threshold, towards full SOAE suppression, the STCs may become even sharper tuned than PTCs, increasing the discrepancy between both tuning measures. Thus, there is no reason to expect that frequency tuning of STCs and PTCs would lead to identical results. Note that our experiment was not intended to show that $Q_{10\text{dB}}$ quality factors of PTC and STC are identical. Rather, it was set up to investigate the relationship between side-lobes in STCs and irregularities in PTCs (Fig. 1).

It is possible that PTC irregularities could result from momentary lapses in attention in the task. We tried to minimize this by presenting a target tone reminder and averaging the threshold over the last six reversals. Evaluating the individual PTCs, the irregularities and dips appear to be present over several neighboring masker frequencies, making it unlikely that we falsely identified, for instance, sudden attention drops as side-lobes. Moreover, we evaluated the reliability of each threshold defining the PTC by calculating the standard deviation across the reversals used to calculate the threshold. While a few irregularities also show enlarged standard deviation at or around the irregularity, most of them did not seem particularly unreliable. It thus seems unlikely that the observed PTC irregularities would be due to momentary attentional deficits.

PTC irregularities were observed, but they did not directly coincide with the presence of STC side-lobes. Moreover, PTC irregularities were also observed in ears without SOAEs present. This suggests that PTC irregularities are not always related to SOAE side-lobes. SOAEs and their STCs are probably determined by the mechanics of the BM and the outer hair cells, whereas the PTC involves the auditory system up to the cortex. Consequently, the origin of side-lobes in STCs and the irregularities in the PTC remains uncertain.

For participants without detectable SOAEs, the probe tone frequency was set to match the probe tone frequency of another subject with SOAE(s). For future studies the probe tone could be matched to the minima of the audiometric fine-structure. Audiometric measurements with high frequency resolution show ripples that are created by auditory threshold minima and maxima (Elliott, 1958). Such ripples are known as audiometric fine-structure (Thomas, 1975). SOAEs are known to correspond to audiometric such minima (Long and Tubis, 1988b; Mauermann et al., 2004; Heise et al., 2008, 2009). Such a minima presumably corresponds to a frequency at which a standing wave could occur, even though there is no detectable SOAE generated.

V. Conclusion

Additional PTC dips are not clearly related to STC side-lobes and can also not exclusively be caused by the presence of other SOAEs. In fact, PTCs of participants without SOAEs were just as irregularly shaped. It may be that different mechanisms lead to STC side-lobes and PTC irregularities. Possibly, applying tonal maskers in PTC measurements instead would compare most closely to the suppressive stimulus in the STC measurement. Future research could use tonal

maskers to measure PTC that involve the suppression of SOAEs at the peripheral level. Across participant groups, Q_{10dB} of the PTC was similar, independently from SOAE presence or absence.

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Captions

FIG. 1. (Color online) Representative STCs and PTCs of seven individuals. In each panel, the horizontal axis displays frequency in kHz. For the plots showing STCs and PTCs, the labels were placed at the emission frequency of interest, and 1 octave below and above that frequency. Each panel on top shows the measurements of frequency selectivity, where (1) the heat map and dark blue contour line indicate 3 dB suppression of the SOAE and (2) the turquoise dotted line with markers represents the PTC of the same participant. The upper panel shows a grid, labeling ± 1 octave from the SOAE frequency. The frequency and level

of the target tone in the PTC measurement are indicated by the green triangle. The corresponding SOAE spectrum is shown underneath the tuning curves. STCs with side-lobes (SL) are shown in panel (A), (B), and (C). Panel (D) and (E) show STC without side-lobes (NSL) while panel (F) and (G) show PTC of participants without SOAEs (No SOAE).

FIG. 2. (Color online) All STCs (panel A) and PTCs (panel B) where curve tips are horizontally aligned to the SOAE frequency and vertically to the tuning curve tip. Per group, the average tuning curves and confidence intervals (95%) are based on generalized additive model (GAM) likelihood-based fits. TCs of the three participant groups are indicated by different line types and colors (online): STCs are indicated with solid lines, PTCs with dashed lines. Participants with STC side-lobes (SL) are presented in dark blue lines, participants without STC side-lobes (NSL) are shown in lighter orange lines, and participants without SOAEs (No SOAE) are illustrated with a purple line. Dots underneath both panels indicate the total SOAE count on the STC (panel A) and PTC (panel B) measurement day. Panel C indicates the STC-PTC comparison of the SL and the NSL group. In the SL group, around 0.5 and 1 oct. above the tip dips can be seen.

FIG. 3. (Color online) Frequency selectivity of the same individuals evaluated via STCs and PTCs. Different subject groups are indicated with different colors: side-lobe group (SL, blue), group without STC side-lobes (NSL, orange), and participants without SOAEs (No SOAE, purple). The middle line in the boxplots indicates the median. The top and lower hinges

indicate the first and third quartile. The whiskers extend to the furthest data point within 1.5 times the interquartile range from the hinges. Individual data points are overlaid on the boxplot. In panel A, for each subject, the filter quality $Q_{10\text{dB}}$ of the STC is shown as a function of the $Q_{0\text{dB}}$ of the PTC. Panel B illustrates the slopes of the tuning curve flanks, below and above the tip (low and high flank, respectively). The orange triangle represents an outlier (at 466.35 dB/oct.) for which the axis is not continuously plotted.







