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Further tests of the local nonlinear interaction-based mechanism for simultaneous suppression of tone burst-evoked otoacoustic emissions.

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ABSTRACT

Tone burst-evoked otoacoustic emission (TBOAE) components measured in response to a 1 kHz tone burst (TB_1) are suppressed by the simultaneous presence of an additional tone burst (TB_2). This "simultaneous suppression of TBOAEs" has been explained in terms of a mechanism based on local nonlinear interactions between the basilar membrane (BM) travelling waves caused by TB_1 and TB_2. A test of this local nonlinear interaction (LNI)-based mechanism, as a function of the frequency separation (Δf, expressed in kHz) between TB_1 and TB_2, has previously been reported by Killan et al. (2012) using a simple mathematical model [Killan et al., Hear. Res. 285, 58-64 (2012)]. The two experiments described in this paper add additional data on the extent to which the LNI-based mechanism can account for simultaneous suppression, by testing two further hypotheses derived from the model predictions. Experiment I tested the hypothesis that TBOAE suppression is directly linked to TBOAE amplitude nonlinearity where ears that exhibit a higher degree of amplitude nonlinearity yield greater suppression than more linear ears, and this relationship varies systematically as a function of Δf. In order to test this hypothesis simultaneous suppression at a range of values of Δf at 60 dB peak-equivalent sound pressure level (p.e. SPL) and TBOAE amplitude nonlinearity from normal human ears was measured. In Experiment II the hypothesis that suppression will also increase progressively as a function of increasing tone burst level was tested by measuring suppression for a range of Δf and tone burst levels at 40, 50, 60 and 70 dB p.e. SPL. The majority of the findings from both experiments provide support for the LNI-based mechanism being primarily responsible for simultaneous suppression. However, some data were inconsistent with this view. Specifically, a breakdown in the relationship between suppression and TBOAE amplitude nonlinearity at Δf = 1 (i.e. when TB_2 was reasonably well separated from, and had a higher frequency than TB_1)

and unexpected level-dependence, most notably at $\Delta f = 1$, but also where $\Delta f = -0.5$, was observed. Either the LNI model is too simple or an alternative explanation, involving response components generated at basal regions of the basilar membrane, is required to account for these findings.

Keywords: Tone burst-evoked otoacoustic emissions, suppression, tone bursts, amplitude nonlinearity

Abbreviations: Basilar membrane, BM; Click-evoked otoacoustic emission, CEOAE; Fast Fourier transform, FFT; Local nonlinear interaction, LNI; peak-equivalent sound pressure level, p.e. SPL; Spontaneous otoacoustic emission, SOAE; Synchronised spontaneous otoacoustic emission, SSOAE; Tone burst-evoked otoacoustic emission, TBOAE; Transient-evoked otoacoustic emission, TEOAE.

1. INTRODUCTION

Transient-evoked otoacoustic emissions (TEOAEs) are physiological signals recorded in the ear canal in response to short duration acoustic stimuli (e.g. Probst et al., 1991; Robinette and Glattke, 2007). Most commonly, TEOAEs are recorded in response to clicks (i.e. click-evoked otoacoustic emissions, CEOAEs), or less commonly tone bursts (i.e. tone-burst-evoked otoacoustic emissions, TBOAEs). In both cases, the presence of a response is reliant on normal functioning of the physiological processes that enhance hearing at low sound levels, known as the cochlear amplifier (e.g. Ashmore et al., 2010). TEOAEs (CEOAEs more so than TBOAEs) are therefore used widely in clinical settings as an assessment of cochlear function.

Based primarily on CEOAE data, two components are thought to be present in the TEOAE response. The first component is characterised by its short latency and near-linear amplitude growth with stimulus level (e.g. Withnell and McKinley, 2005; Withnell et al., 2008; Goodman et al., 2011; Moleti et al., 2012). Because of its short latency, this component is assumed to be generated at basal regions of the basilar membrane (BM) via two possible mechanisms; nonlinear intermodulation distortion (e.g. Yates and Withnell, 1999; Carvalho et al., 2003; Withnell and McKinley, 2005; Notaro et al., 2007; Withnell et al., 2008) and linear reflection (Goodman et al., 2011; Moleti et al., 2012; Sisto et al., 2013). Recent modelling efforts suggest that the second of these mechanisms, the basal-reflection mechanism, is most likely to account for the short-latency, basal-source component (Moleti et al., 2013). The second, long-latency component exhibits compressive growth with stimulus level and frequency-dependent latency that is consistent with its generation via linear

reflection at the peak region of the travelling wave (Shera, 2004; Sisto and Moleti, 2007; Sisto and Moleti, 2008; Withnell et al., 2008). The presence of this second component is compatible with the existence of compressive "generator channels" tonotopically distributed along the BM. TEOAE components are assumed to be generated locally within these channels (i.e. at their characteristic place) in response to stimulus components at the same frequency (e.g. Kemp and Chum, 1980; Tavartkiladze et al., 1994; Zettner and Folsom, 2003; Kalluri and Shera, 2007). This local, long-latency component dominates the overall TEOAE response at lower stimulus levels, whilst at higher levels the basal-source component dominates (Withnell et al., 2008; Goodman et al., 2011; Moleti et al., 2012; Sisto et al., 2013).

TEOAEs exhibit a number of suppression behaviours. Previous investigators (Yoshikawa et al., 2000; Killan et al., 2012) have shown that the amplitude of a TBOAE recorded from normal human ears in response to a 1 kHz tone burst (TB_1) can be suppressed by the simultaneous presence of an additional (equal level and phase) tone burst (TB_2). Specifically, components at 1 kHz in the response obtained to simultaneous presentation of TB_1 and TB_2 were reduced in amplitude compared to the corresponding components in the response obtained by (offline) summation of the individual responses to TB_1 and TB_2. Findings presented by Yoshikawa et al. (2000) show that where TB_2 had a higher centre frequency than TB_1, the amount of suppression increased as a function of decreasing frequency separation between the centre frequencies of TB_1 and TB_2 (referred to here as Δf and expressed in kHz). Killan et al. (2012) showed a similar dependence of suppression on Δf for higher frequency TB_2 (i.e. when Δf = 0.5, 1 and 2). In addition they demonstrated that greatest suppression tended to occur when TB_2 had the same frequency as TB_1 (i.e. $\Delta f = 0$), with a reduction in suppression observed when TB_2 had a lower frequency than TB_1 (i.e. $\Delta f = -0.5$).

Different mechanisms have been proposed to account for this "simultaneous suppression of TBOAEs". One view states that when TB_2 has a higher centre frequency than TB_1, its simultaneous presence somehow interferes with the generation of basal-source components in the response evoked by TB_1 (Xu et al., 1994; Yates and Withnell, 1999), although the detail of this interference is unclear. Further, the finding that suppression progressively increases as Δf decreases so that maximum suppression was measured when TB_1 and TB_2 had the same frequency, is at odds with the involvement of basal-source components. If basal-source components were responsible for suppression then it could be argued that maximum suppression would occur when TB_2 had a higher frequency than TB_1. Similarly, it is not clear how TB_2 is able to cause suppression of TB_1 response components when TB_2 had a lower frequency than TB_1. An alternative mechanism states that simultaneous suppression of TBOAEs results from local nonlinear interactions between the BM travelling waves caused by TB_1 and TB_2 (Killan and Kapadia, 2006; Killan et al., 2012). This local nonlinear interaction (LNI)-based mechanism assumes the dominant component of the TBOAE response is the long-latency component that originates from compressive generator channels located at the tonotopic place. Specifically, Killan et al. (2012) argued if TB_1 and TB_2 are closely spaced in frequency (i.e. $\Delta f = -0.5$ or 0.5) then their travelling waves would overlap following simultaneous presentation. As a result, both TB_1 and TB_2 will cause excitation of generator channels at BM sites tuned to those between the centre frequencies of TB_1 and TB_2. These generator channels will therefore experience increased excitation with simultaneous presentation compared to individual presentation of TB_1 and TB_2. However, because generator channels are compressive, TBOAE components output from these channels will have smaller amplitude than the corresponding components in the offline sum of the individual responses, and suppression of the simultaneous response will be observed.

Greatest suppression would be expected when TB_1 and TB_2 had identical centre frequencies, with TB_1 and TB_2 well-separated in frequency causing least suppression. This LNI-based mechanism is able to account for the Δf-dependence of suppression, including the finding that a lower frequency TB_2 was able to cause suppression of the TB_1 response. This is less straightforward to explain in terms of a basal-source component mechanism. The LNI-based mechanism is similar to mechanisms proposed to explain other TEOAE suppression phenomena (Kemp and Chum, 1980; Kapadia and Lutman, 2001; Harte et al., 2005; Lineton et al., 2006; Thornton et al., 2006).

The extent to which the LNI-based mechanism can account for simultaneous suppression of TBOAEs has previously been tested using a simple mathematical model (Killan et al., 2012). This model incorporated a single generator channel represented by a static gammachirp filter with peak frequency at 1.2 kHz, in series with a static compressive input-output function. This input-output function allowed the nonlinearity of the generator channel to be varied in accordance with reports of TBOAE amplitude nonlinearity reported in the literature. Pairs of TB_1 and TB_2 at a range of values of Δf were applied to the model to obtain prediction of simultaneous suppression. The aim of the model was to provide a simple indication of the LNI-based mechanism for a single generator channel located in the region of 1 kHz, rather than accurately represent the physiological process that occur in the cochlea following simultaneous stimulation TB_1 and TB_2. The predictions of the model were compared with TBOAE suppression data recorded from normal human ears for the same values of Δf. A close agreement between the model predictions and mean TBOAE suppression was taken to indicate that the LNI-based mechanism was responsible for simultaneous suppression of TBOAEs.

Though not tested by Killan et al. (2012), their model also predicted that suppression governed by the LNI-based mechanism would be dependent on generator channel nonlinearity so that larger amounts of suppression would be expected when the generator channel was more nonlinear, compared to when the channel was relatively linear. Further, the model predicted that this channel nonlinearity-dependence would vary as a function of Δf so that for the same increase in nonlinearity, greater levels of suppression would be evident at smaller values of Δf compared to higher values of Δf. This is understood in terms of suppression being dependent on generator channel nonlinearity *and* the amount of overlap between the excitation patterns caused by TB_1 and TB_2. A manifestation of generator channel nonlinearity is the nonlinear growth of TBOAE amplitude with increasing tone burst level, typically observed via TBOAE level functions (e.g. Rutten, 1980; Johnsen and Elberling, 1982; Elberling et al., 1985; Norton and Neely, 1987; Epstein and Florentine, 2005). It therefore follows that ears exhibiting a high degree of TBOAE amplitude nonlinearity should yield greater suppression than ears exhibiting less nonlinearity, and that this relationship will vary systematically as a function of Δf.

A second, related prediction can also be derived from the relationship between suppression and TBOAE amplitude nonlinearity. Because TBOAE amplitude nonlinearity is compressive (i.e. it becomes increasingly nonlinear with increasing stimulus level until saturation is reached), suppression governed by the LNI-based mechanism will also increase as a function of increasing tone burst level, for increases below the level at which saturation occurs. To date, no data have been reported that allow investigation of the effect of tone burst level on simultaneous suppression of TBOAEs caused by an additional single tone burst. Previously

reported data for pairs of TB_1 and TB_2 were obtained for only a small range of levels. Yoshikawa et al. (2000) measured suppression at only two levels (60 and 70 dB p.e. SPL), whilst Killan et al. (2012) measured suppression at a only 60 dB p.e. SPL. Other authors have presented simultaneous suppression data measured over a range of levels for an additional *pair* of tone bursts, i.e. TB_1, in combination with TB_2 and TB_3 (Xu et al., 1994; Killan and Kapadia, 2006). However, it is possible that interactions between TB_2 and TB_3 (that cannot occur when TB_2 alone is presented with TB_1) influence suppression of the response to TB_1, such that the findings of these investigations cannot be generalised to the case of TB_1 with TB_2 alone.

An understanding of the mechanism underpinning simultaneous suppression of TBOAEs has important implications for the interpretation of TBOAEs in clinical settings. If, as is the case for the LNI-based mechanism, simultaneous suppression is caused by nonlinear interactions occurring locally at the characteristic place of the suppressed components, TBOAE can be considered to provide a place- and frequency-specific assessment of cochlear function. Such specificity cannot be assumed if simultaneous suppression instead reflects the significant involvement of components generated at remote basal BM locations. This paper therefore describes two experiments undertaken to determine whether simultaneous suppression of TBOAEs can be fully explained by the simple LNI-based model, or whether either a more complex model or alternative mechanisms, such as those involving basal-source components need to be considered. Experiment I measured simultaneous suppression (at a range of values of Δf) and TBOAE amplitude nonlinearity from a number of normal human ears in order to determine the extent of the predicted relationship between simultaneous suppression of TBOAEs and TBOAE amplitude nonlinearity. A similar approach was followed by Thornton et al. (2006) to investigate the mechanisms responsible for CEOAE suppression

caused by very high click presentation rates. Experiment II provides a description of suppression as a function of an extended range of tone burst levels and tests the predicted level-dependence of suppression, again in normal human ears. In both experiments, the degree of agreement between the model-derived predictions and TBOAE data was used to demonstrate the extent to which the LNI-based model can account for simultaneous suppression. It was reasoned that any substantial differences would argue either that the model was too simple or against the LNI-based mechanism being solely responsible for suppression.

2. EXPERIMENT I: Testing the link between TBOAE amplitude nonlinearity and simultaneous suppression of TBOAEs

2.1. Materials and methods

2.1.1. Subjects

Thirteen (7 female, 6 male) normally hearing adults aged between 18 and 33 years (median = 25 years) participated in this study. All subjects had hearing threshold levels of 15 dB or better at octave frequencies between 0.25 and 8 kHz and normal middle ear function as confirmed by tympanometry. One ear of each subject was chosen for testing (7 right, 6 left). Because it has been suggested that spontaneous otoacoustic emissions (SOAEs) can influence the nonlinear behaviour exhibited by TEOAEs (e.g. Probst et al., 1986; Kulawiec and Orlando, 1995), ears that exhibited synchronised SOAEs (SSOAEs), as measured using the Otodynamics ILO 292 system (London, UK), were not included.

2.1.2. Instrumentation and stimuli

All TBOAE recordings were made using a custom-built system previously described by Killan et al. (2012). Purpose-written software controlled the synchronised input and output of a RME HDSP 9632 personal computer soundcard (Haimhausen, Germany). Stimuli were presented via the earphone of a commercially available Otodynamics (London, UK) probe via a purpose-built amplifier. The signal measured by the probe microphone was input to the soundcard via a second amplifier and high-pass filter (cut-off at 500 Hz with roll-off slopes >12dB/octave). This input signal was sampled at a rate of 24 kHz and time-averaged

within two separate buffers. This created two replicate recordings, each resulting from 250 averages. These were stored on disk and analysed offline.

Simultaneous suppression of TBOAEs was measured in accordance with the test paradigm described by Killan et al. (2012). Tone bursts were cosine-windowed sinusoids (rise-fall = 2.5 ms; plateau = 0 ms) and were presented in pairs (TB_1 and TB_2) either sequentially or simultaneously. Simultaneous presentation was achieved via a complex stimulus resulting from the digital addition of a pair of TB_1 and TB_2. TB_1 had a fixed centre frequency of 1 kHz whereas TB_2 had a centre frequency of 0.5, 1, 1.5, 2 or 3 kHz. This resulted in five values of Δf ($TB_2 - TB_1$): −0.5, 0, 0.5, 1 and 2.[1] The inclusion of $\Delta f = 0$ (identical TB_1 and TB_2 and simultaneous presentation being equivalent to doubling the amplitude of TB_1) represents a special case where suppression can be assumed to be a sole consequence of TBOAE amplitude nonlinearity against which results obtained at other Δf can be compared.

All tone bursts were presented using linear averaging at 60 dB p.e. SPL (as calibrated within a passive 2 cm^3 cavity) and a rate of 50/s. This level was chosen for two reasons. First, preliminary testing had shown that it corresponded to approximately 45 dB sensation level (SL) and as such the response characteristic of the cochlea could be assumed to be nonlinear (e.g. Kim et al., 1980; Nuttall and Dolan, 1996; Patuzzi, 1996; Rhode and Recio, 2000; Ren, 2002; Gorga et al., 2007). Second, the method used for estimating TBOAE level function gradient is considered to be most accurate at the mid-point of the level function (e.g.

[1] The negative value of Δf simply indicates that the centre frequency of TB_2 was lower than TB_1.

Thornton et al., 2006). For the range of tone burst levels used to generate level functions (see below) this corresponded to approximately 60 dB p.e. SPL.

For each subject, an estimate of TBOAE amplitude nonlinearity was derived from the gradient of their TBOAE level function. The stimulus used to generate TBOAE level functions was TB_1 presented at 40, 46, 50, 56, 60, 66, 70 and 76 dB p.e. SPL.

2.1.3. Procedure

Prior to testing, all subjects gave informed consent in accordance with the requirements of the School of Healthcare Research Ethics Committee. For each subject, simultaneous suppression of TBOAEs and level function measurements were made during a single recording session, lasting approximately 30 minutes. All TBOAE measurements were made in a sound-attenuated room, with the subject comfortably seated and instructed to remain quiet and still. For the duration of testing the probe was sealed in the ear canal with a soft plastic tip and was taped in position. Simultaneous suppression measurements were always made first, followed by those used to generate TBOAE level functions. In order to minimise potential order effects, for each pair of TB_1 and TB_2, sequential and simultaneous presentations occurred in a random order, as was the case for the five pairs of TB_1 and TB_2. Tone bursts were confirmed to be stable throughout the recording session for each subject by comparison of TB_1 waveforms across all five pairs. The presentation order of the eight levels of TB_1 used to generate level functions was also randomised.

2.1.4. Analysis

In order to calculate simultaneous suppression of TBOAEs, a mean response waveform was calculated for all TB_1, TB_2 and complex stimuli. Pairs of mean TB_1 and TB_2 response waveforms were then summed to form five "composite" response waveforms. To minimise the influence of linearly scaling stimulus ringing components, each composite and complex waveform was time-windowed so that the first 8 ms (post-stimulus onset) of each waveform was discarded from subsequent analysis. The absence of stimulus ringing at latencies longer than 8 ms was confirmed by measurements made in a passive 2 cm^3 cavity. Removal of such a substantial portion of the waveform is not unusual when recording TBOAEs (e.g. Rutten, 1980; Prieve et al., 1996; Killan and Kapadia, 2006), but is done at the cost of TBOAE response components with latencies shorter than 8 ms. Frequency spectra (in dB SPL/Hz) were then calculated using a 512-point fast Fourier transform (FFT) from the time-windowed composite and complex response waveforms. Noise spectra were also calculated from the five complex responses. To ensure that any differences subsequently observed between the composite and complex TBOAE spectra arose from points in the spectra clear of the noise floor, the TBOAE spectra were 'clipped' at the corresponding noise floors by replacing any values below the noise floor by the value of the noise spectrum at that frequency. The complex noise spectrum was used to clip both composite and complex spectra because results of pilot testing had shown that the greatest noise levels were contained within the complex response.

Suppression (in dB) was then estimated as the mean difference in spectral level (composite – complex) within an arbitrary 375 Hz-wide frequency band centred at a region of suppression. Regions of suppression were individually identified for each value of Δf and for each subject

via visual inspection of the composite and complex spectra obtained at 60 dB p.e. SPL. This approach allowed for the predicted variation in the frequencies at which suppression occurred as a function of Δf, as well as considerable between subject-variation (e.g. Probst et al., 1986; Xu et al., 1994; Yoshikawa et al., 2000; Killan and Kapadia, 2006). Such variation resulted in a single frequency band for all ears and values of Δf being insensitive to systematic changes in suppression. For all ears and all values of Δf, the centre of the frequency bands was always located in the region of the 1 kHz spectral peak, between 0.75 and 1.5 kHz, and was always between the centre frequencies of TB_1 and TB_2, i.e. in the approximate region of overlap of the two tone bursts. The choice of bandwidth (375 Hz) was wide enough to measure systematic changes in suppression, whilst minimising the influence of non-systematic changes in spectral level at more remote frequencies. In terms of the LNI-based model, this approach can be viewed as measuring suppression for the local generator channel whose output exhibits greatest suppression in response to a specific pair of TB_1 and TB_2.

Preliminary analysis demonstrated that whilst responses to TB_1 were stable across recordings, small non-systematic differences in spectral level were sometimes evident. A "suppression threshold", above which changes in TBOAE level caused by the simultaneous presentation of TB_2 could be considered to be material suppression, was therefore calculated. This was defined for each subject as the mean difference in spectral level between the individual responses to TB_1 and TB_2 when $\Delta f = 0$.

TBOAE level functions were generated from the responses obtained to TB_1 presented at eight levels. Again, in order to minimise the effect of stimulus ringing, the first 8 ms of the TBOAE waveforms was removed. Frequency spectra (using a FFT) of the time-windowed

mean response at each level were calculated. These were visually inspected to identify a dominant peak in the region of 1 kHz. At each of the eight levels of TB_1, TBOAE amplitude was estimated as the mean spectral level within an arbitrary 560 Hz-wide frequency band centred at this peak. This approach allowed for between-subject variation in spectral morphology. The bandwidth of the frequency band (560 Hz) included the low and high frequency slopes of the 1 kHz peak where compressive growth was observed. TBOAE amplitude (in dB SPL/Hz) was plotted against TB_1 level (in dB p.e. SPL). Estimates of noise levels, calculated from the difference between the replicate response waveforms, were also made and plotted on the level functions as a representation of the noise floor at each level. TBOAE amplitude nonlinearity was then estimated from the gradient (in dB/dB) of a regression line fitted to the TBOAE level function (e.g. Norton and Neely, 1987; Prieve et al., 1996; Lineton et al., 2006; Thornton et al., 2006). A level function with a gradient of 1 dB/dB would indicate linear TBOAE amplitude growth, whereas gradients less than 1 dB/dB would indicate compressive amplitude nonlinearity, with increasing nonlinearity indicated by gradients approaching 0 dB/dB.

Suppression-nonlinearity functions (scatter-plots showing the amount of suppression as a function of TBOAE amplitude nonlinearity for all thirteen ears) were generated at each value of Δf. The gradient of these suppression-nonlinearity functions was then used to provide a measure of the extent of the relationship between suppression and TBOAE amplitude nonlinearity at each Δf. Because increasing TBOAE amplitude nonlinearity is indicated by progressively smaller values, suppression-nonlinearity functions with negative gradients were expected.

A combination of standard correlation analysis and two-level regression modelling was applied to the data (e.g. Gilthorpe et al., 2000; Goldstein, 2011; Snijders and Bosker, 2011). The levels of the model were measurement (within-subject level) and subjects. Variance is partitioned across the subject and measurement levels via random variables (residuals) associated with the intercept term, [2] such that whilst each subject has the same linear relationship between the dependent variable (suppression) and the explanatory variables (Δf, TBOAE amplitude nonlinearity) they each have a different intercept. The models are therefore able to incorporate the clustering of data inherent in repeated measures experimental designs, and avoid violating the assumption of independence of data that underpins single-level regression methods. Models were estimated by the maximum likelihood method via an iterative generalised least squares procedure (e.g. Goldstein, 1986). This allowed an estimate of model deviance to be made. The difference between deviance of two models (that differ simply by the addition of explanatory variables) can be used as a test statistic to determine the effect of the additional explanatory variable on suppression (e.g. Snijders and Bosker, 2011). This deviance statistic has a χ^2 distribution with degrees of freedom equal to the difference in number of variables included in the two models. In addition, regression coefficients were tested for significance via the Wald test.

[2] An assumption of such modelling is that the random residuals at each level are normally distributed with zero mean. This was confirmed via visual inspection of normal probability plots.

2.2. Results and discussion

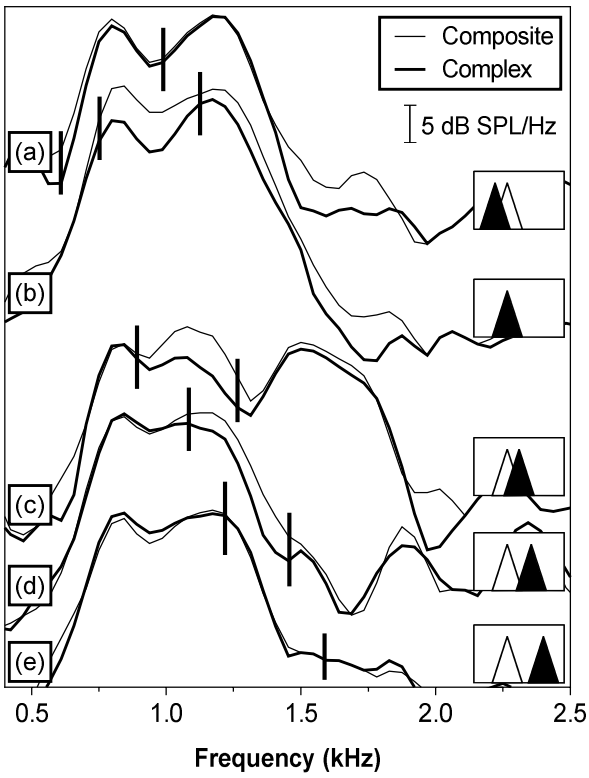

Figure 1. Composite (fine line) and complex (bold line) spectra obtained from an individual ear at Δf = (a) −0.5, (b) 0, (c) 0.5, (d) 1 and (e) 2. The inset alongside each pair of spectra provides a schematic representation of the frequency separation between TB_1 and TB_2 as described in the main text. The pairs of vertical lines indicate the 375 Hz wide frequency band used to calculate suppression for each Δf. Spectra are offset on the *y* axis for clarity and the scale bar represents 5 dB SPL/Hz.

Fig. 1 shows the frequency spectra calculated from the composite (fine line) and complex (bold line) responses recorded from an individual ear. Pairs of spectra are shown for Δf = (a) −0.5, (b) 0, (c) 0.5, (d)1 and (e) 2, with the 375 Hz frequency band used to calculate suppression in each case represented by a pair of vertical lines. The frequency band is seen to shift to higher frequencies as a function of increasing Δf, whilst remaining within the region of the 1 kHz response peak. A schematic representation of the frequency separation between TB_1 (open triangle) and TB_2 (filled triangle) is also shown adjacent to each pair of spectra.

These serve simply to provide a visual reference for the proximity of TB_1 and TB_2 in terms of their centre frequency. They do not intend to provide detail as to how TB_1 and TB_2 interact on the BM. In the case of $\Delta f = 0$, where TB_1 and TB_2 have the same centre frequency, only a single triangle is shown. Visual inspection of Fig. 1 reveals that at each Δf, whilst the composite and complex spectra contain peaks approximately corresponding to the frequencies of TB_1 and TB_2, suppression is clearly evident as a reduction in level of the peak at 1 kHz in the complex response. For all five Δf suppression occurs at frequencies between the centre frequencies of TB_1 and TB_2. The same trend is evident in Fig. 2 which shows the mean spectra ($n = 13$) obtained at Δf = (a) −0.5, (b) 0, (c) 0.5, (d) 1 and (e) 2. Figs. 1 and 2 also show the amount of suppression varies as a function of Δf, with greatest suppression at $\Delta f = 0$ and 0.5, with a progressive reduction in suppression observed as Δf increases towards $\Delta f = 2$. At $\Delta f = -0.5$ suppression is substantially less than that observed at $\Delta f = 0$ and 0.5. This pattern of suppression is confirmed by Fig. 3 (a) and (b). Fig. 3 (a) shows the suppression-Δf function obtained for the individual ear shown in Fig. 1, and (b) the mean suppression-Δf function ($n = 13$). The Δf-dependence of suppression observed is consistent with that described by Killan et al. (2012), though the present findings show greater levels of suppression. This difference is a consequence of different methods being used to estimate suppression. Whereas the present experiment estimated suppression from frequency spectra using frequency bands that varied between ears and Δf, Killan et al. (2012) measured suppression for all ears and Δf directly from time waveforms filtered between 0.7 and 1.3 kHz. Killan and Kapadia (2006), who also estimated suppression within discrete bands of the response frequency spectra, reported similar level of suppression to those reported here.

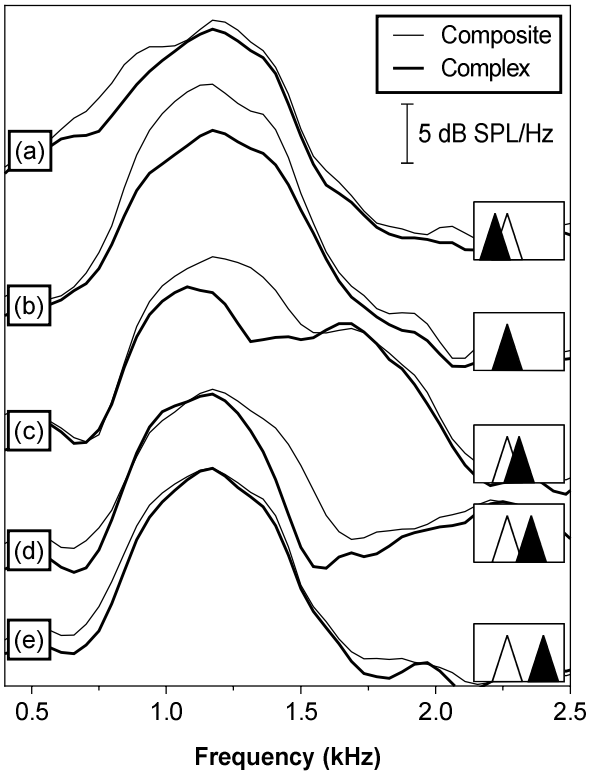

Figure 2. Mean composite (fine line) and complex (bold line) spectra (n = 13) at Δf = (a) −0.5, (b) 0, (c) 0.5, (d) 1 and (e) 2. The inset shown in each panel is the same format as that described for Figure 1. Spectra are offset on the y axis for clarity and the scale bar represents 5 dB SPL/Hz.

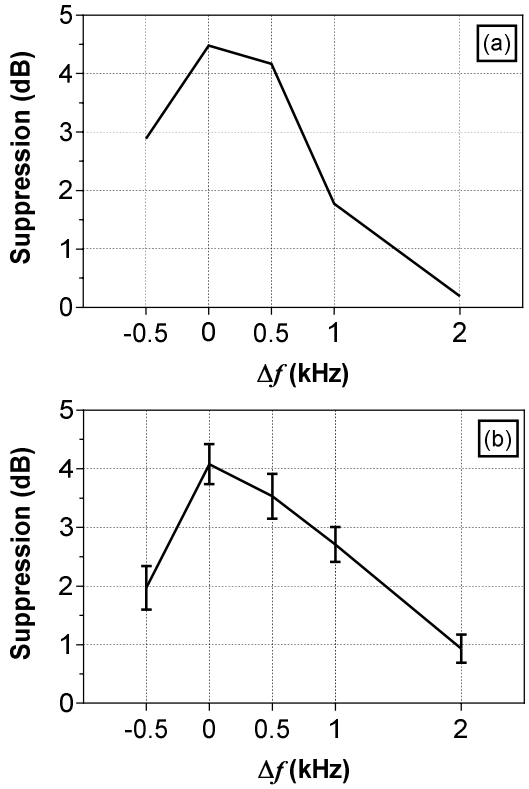

Figure 3(a). The suppression-Δf function for the individual ear shown in Figure 1. (b) Mean TBOAE suppression-Δf function (n = 13). Error bars represent ± 1 SE of the mean.

An example TBOAE level function is shown in Fig. 4. The bold dashed line at −14.7 dB SPL/Hz represents the mean + 1 standard deviation of the noise level recorded at each of the eight levels. At all eight levels, the TBOAE was clear of this estimate of the noise floor. The figure also shows the regression line from which TBOAE amplitude nonlinearity was estimated. For the ear shown, the gradient of this line was 0.39 dB/dB (r = 0.97). Across all thirteen ears, level function gradients ranged from 0.30 dB/dB (i.e. most nonlinear) to 0.65 dB/dB (i.e. least nonlinear), with a mean of 0.44 dB/dB. For all ears, r values greater than 0.95 were obtained. Such estimates of TBOAE amplitude nonlinearity are consistent with those previously reported (e.g. Rutten, 1980; Johnsen and Elberling, 1982; Elberling et al., 1985; Norton and Neely, 1987; Epstein and Florentine, 2005).

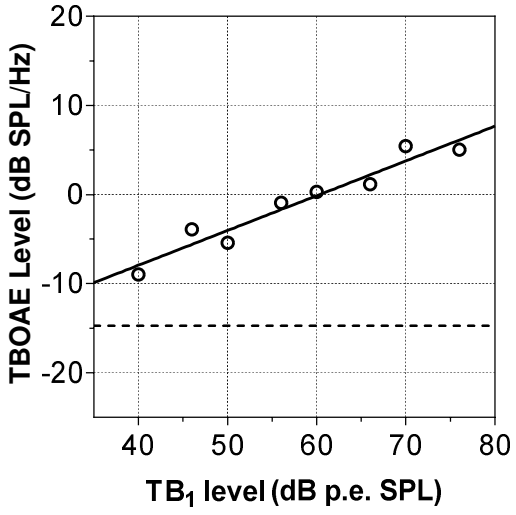

Figure 4. A TBOAE level function (and regression line) measured from an individual ear. The dashed horizontal bold line represents the mean +1 standard deviation of the noise floor across all eight TB_1 levels tested.

Fig. 5 (a) through (e) show the suppression-nonlinearity functions obtained at Δf = 0, −0.5, 0.5, 1 and 2 respectively. The schematic representation of the frequency separation between TB_1 and TB_2 is shown in each panel. The horizontal dashed line in each panel at approximately 0.9 dB is the mean +1 standard deviation of the estimated suppression threshold. Suppression above this threshold was considered to be material, rather than resulting from non-systematic variation in the level of the TBOAE. Also shown in each panel is a regression line. The gradient of this line was used as an estimate of the extent of the relationship between suppression and TBOAE amplitude nonlinearity. Only ears that exhibited suppression greater than the threshold at 0.9 dB were used in calculating the regression lines.

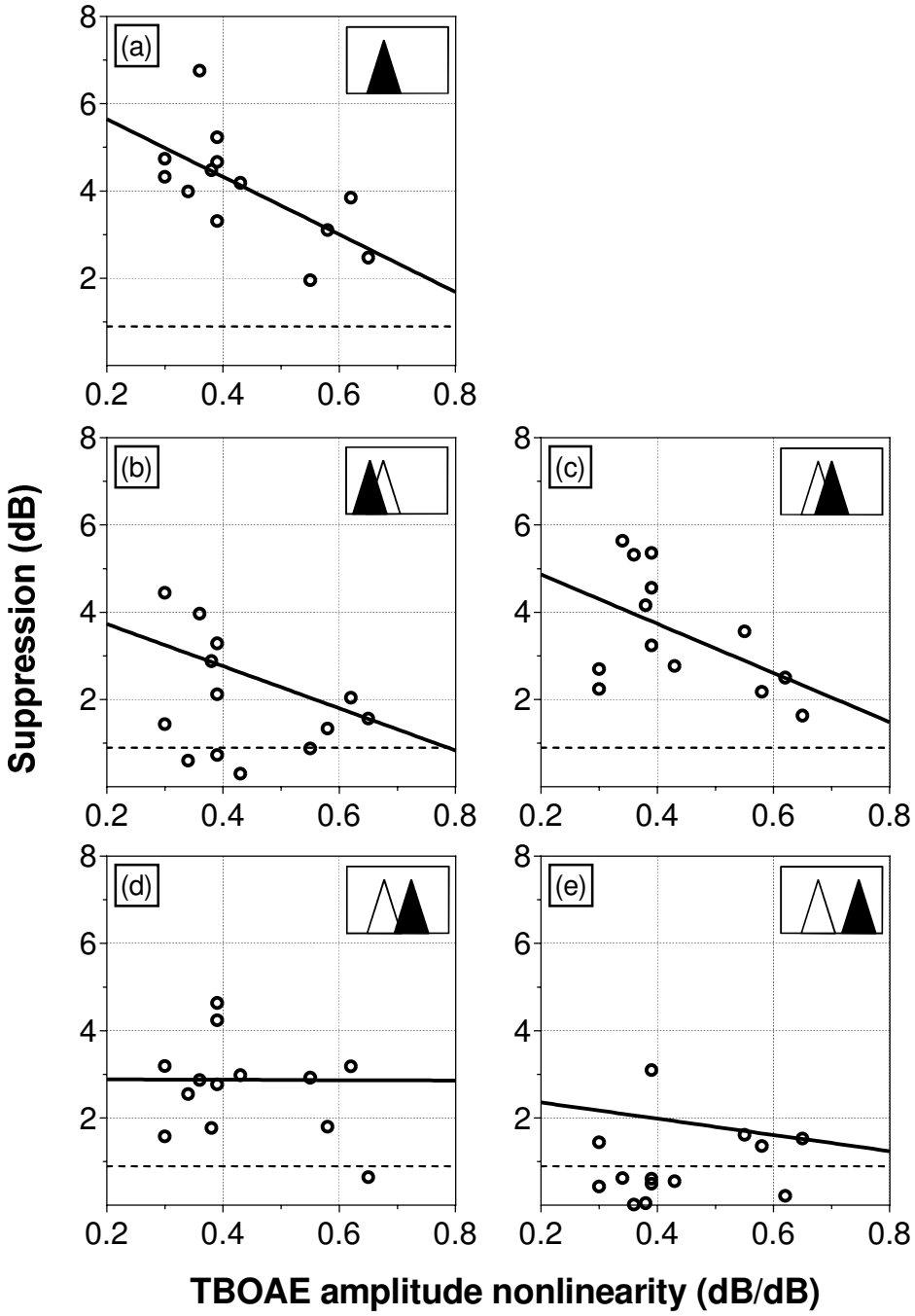

Figure 5. Suppression-nonlinearity functions obtained at Δf = (a) 0, (b) −0.5, (c) 0.5, (d) 1 and (e) 2. The inset shown in each panel is the same format as that described for Figure 1. The dashed horizontal line represents the suppression threshold. Each panel also shows the regression line fitted to the data-points greater than the suppression threshold.

Panel (a) of Fig. 5 shows the suppression-nonlinearity function at $\Delta f = 0$, i.e. the special case where suppression is a sole consequence of TBOAE amplitude nonlinearity. Consistent with this, a clear tendency is evident for suppression in ears that exhibit greatest TBOAE amplitude nonlinearity to be greater than suppression measured in less nonlinear ears. This is confirmed by a regression line with gradient of −6.6 dB ($r = -0.65$, $p < 0.05$). A similar trend is also evident at $\Delta f = 0.5$ (panel (c)), i.e. when TB_2 had a slightly higher centre frequency than TB_1. The gradient of the function in this case was −5.6 dB ($r = -0.50$, $p < 0.05$). Panel (b) shows the suppression-nonlinearity function obtained at $\Delta f = -0.5$, i.e. when TB_2 had a slightly lower centre frequency than TB_1. Inspection shows that four of the thirteen ears yielded suppression below the suppression threshold. This is despite three of these ears exhibiting a relatively high degree of TBOAE amplitude nonlinearity, and as such would be expected to exhibit relatively large amounts of suppression. A possible explanation, based on previous reports of a number of suppression phenomena that consistently demonstrate higher frequency stimuli to be more effective suppressors than lower frequency stimuli (e.g. Brass and Kemp, 1993; Cooper and Rhode, 1996; Rhode and Recio, 2000; Yoshikawa et al., 2000; Killan and Kapadia, 2006; Keefe et al., 2008), is that the main suppression effect seen at $\Delta f = -0.5$ occurs in the region of 0.5 kHz, as opposed to 1 kHz. That is, because in this case TB_1 has a higher frequency than TB_2, TB_1 acts as the suppressor. Because the analysis employed in this investigation focussed on suppression in the region of 1 kHz, such suppression would not have been measured. For the nine ears that did exhibit material suppression, a similar trend to that seen at $\Delta f = 0$ and 0.5 is evident, though the gradient of −4.8 dB ($r = -0.58$, $p = 0.05$) was less steep than at $\Delta f = 0$ and 0.5. The findings at $\Delta f = -0.5$ and 0.5 therefore demonstrate agreement with the predictions of the LNI-based model.

Panel (e) shows the suppression-nonlinearity function obtained at $\Delta f = 2$, i.e. when TB_2 had a substantially higher centre frequency than TB_1. Inspection of the function shows only five ears exhibited suppression greater than 0.9 dB, and the suppression obtained from those ears was small compared with suppression obtained at the other values of Δf. This is consistent with the LNI-based model which predicts that since there is little or no overlap between the travelling waves caused by TB_1 and TB_2, there will be little or no suppression at $\Delta f = 2$. , The suppression-nonlinearity function from the five ears that exhibited material suppression had a gradient of −1.9 dB ($r = -0.44$, $p = 0.16$). This weak relationship is in keeping with the LNI-based model.

The results obtained at $\Delta f = 1$, i.e. when TB_2 is a relatively well-separated and higher frequency tone burst than TB_1, are shown in panel (d). The suppression-nonlinearity function shows that substantial amounts of suppression were measured from ears exhibiting both relatively high and low TBOAE amplitude nonlinearity, resulting in a near-horizontal regression, i.e. with gradient of approximately 0 dB ($r = -0.01$, $p = 0.49$). Thus, in contrast to the results obtained at $\Delta f = -0.5$, 0.5 and 2, no clear relationship between suppression and TBOAE amplitude nonlinearity is apparent, despite substantial amounts of suppression being obtained. This is inconsistent with the predictions of the LNI-based model which predicts a similar but weaker relationship between suppression and TBOAE amplitude nonlinearity to that seen at $\Delta f = -0.5$ and 0.5.

Finally, the above observations regarding suppression-nonlinearity functions are further confirmed by the results of the two-level regression modelling. The inclusion of TBOAE amplitude nonlinearity caused a significant reduction in model deviance ($\chi^2 = 5.73$, $df = 1$, p

< 0.05).[3] Further, the inclusion of the interaction between Δf and TBOAE amplitude nonlinearity showed that the effect of TBOAE amplitude nonlinearity was significant only at $\Delta f = 0$ ($t = 2.43$, $p < 0.01$) and $\Delta f = 0.5$ ($t = 2.13$, $p < 0.05$). At $\Delta f = -0.5$ the effect approached significance ($t = 1.49$, $p = 0.07$), whilst at $\Delta f = 1$ ($t = 1.24$, $p = 0.11$) and 2 ($t = 0.52$, $p = 0.30$) it was non-significant.

[3] Prior to including TBOAE amplitude nonlinearity, between-subject explanatory variables of sex ($\chi^2 = 0.56$, $df = 1$, $p = 0.45$), age ($\chi^2 = 0.08$, $df = 1$, $p = 0.78$), mean hearing threshold level ($\chi^2 = 0.02$, $df = 1$, $p = 0.88$) and ear ($\chi^2 = 0.02$, $df = 1$, $p = 0.89$) were shown to be non-significant.

3. EXPERIMENT II: Testing the effect of tone burst level on simultaneous suppression of TBOAEs

3.1. Methods and materials

3.1.1. Subjects

Six subjects (four female, two male) from the thirteen used in Experiment I were tested. These subjects exhibited repeatable and stable TBOAEs at 40 dB p.e. SPL (i.e. the lowest of the four levels for which suppression was to be measured). Subjects were aged between 18 and 33 years (median = 22.5 years). One ear was tested (two right, four left) from each subject.

3.1.2. Instrumentation and stimuli

Simultaneous suppression of TBOAEs was measured using the same custom-built system and test paradigm described for Experiment I. TB_1 and TB_2 were presented in equi-level pairs, either sequentially or simultaneously, where TB_1 had a fixed centre frequency of 1 kHz and TB_2 had a centre frequency of 0.5, 1, 1.5, 2 or 3 kHz, resulting in the five values of Δf, i.e. −0.5, 0, 0.5, 1 and 2. As was the case in Experiment I, suppression measured at $\Delta f = 0$ is considered an exemplar case against which suppression at other Δf can be compared. Specifically for this experiment, the level-dependence of suppression is expected to be most pronounced at $\Delta f = 0$. This is because suppression at $\Delta f = 0$ is assumed to be a sole consequence of TBOAE amplitude nonlinearity, and the level-dependence of suppression is predicted as a reflection of corresponding changes in TBOAE amplitude nonlinearity. All

TB_1 and TB_2 were presented linearly at 40, 50, 60 and 70 dB p.e. SPL (as calibrated within a passive 2 cm^3 cavity) and a rate of 50/s.

3.1.3. Procedure

For each subject, TBOAE recordings were made during a single recording session that took place in a sound-attenuated room and lasted approximately 40 minutes. For the duration of the session the measurement probe was sealed in the ear canal with a soft plastic tip and was taped in position. Stimulus stability was confirmed for each subject at each level by comparison of the TB_1 waveforms within each of the five pairs. Again, the presentation of TB_1 and TB_2 was randomised in order to minimise potential order effects.

3.1.4. Analysis

To estimate simultaneous suppression of TBOAEs, composite, complex and noise spectra were calculated from the time-windowed (8 to 20 ms) response waveforms in accordance with the method employed in Experiment I. Suppression (estimated as the mean difference between composite and complex spectra within a 375 Hz-wide frequency band) was then calculated at each value of Δf and each of the four tone burst levels. For each subject and at each at Δf the location of the frequency band was centred at an identified region of suppression within the spectra obtained at 60 dB p.e. SPL. In addition to suppression, the suppression threshold, as described for Experiment I, was again estimated.

To observe the effect of tone burst level on suppression, suppression-level functions were generated at each Δf. These functions plot suppression against tone burst level. Statistical analysis was achieved using a similar two-level regression model to that used in Experiment I. Suppression was again the dependent variable with Δf and tone burst level the main explanatory variables.

3.2. Results and discussion

Fig. 6 shows the mean composite and complex spectra (n = 6) obtained when Δf = (a) 0, (b) −0.5, (c) 0.5, (d) 1 and (e) 2 at tone burst levels of (i) 70, (ii) 60, (iii) 50 and (iv) 40 dB p.e. SPL. The same schematic representation of the frequency separation between TB_1 (open triangle) and TB_2 (filled triangle) used in previous figures is also used here. At all four levels suppression of the complex response is clearly evident at and around the dominant peak located at approximately 1 kHz. Visual inspection reveals the same pattern of Δf-dependence seen in Fig 3 (a) and (b), as well as a tendency for suppression to increase as a function of tone burst level. This trend is more clearly seen in Fig. 7 (a) through (e) which shows the suppression-level functions obtained from a representative ear at each value of Δf. Panel (a) shows the suppression-level function obtained at Δf = 0. The progressive increase observed is expected assuming that suppression at Δf = 0 is a sole consequence of TBOAE amplitude nonlinearity. Panels (b) through (e) show the suppression-level functions obtained from the same ear at Δf = −0.5, 0.5, 1 and 2 respectively. At Δf = −0.5 (panel (b)), the overall trend was for suppression to increase with tone burst level, though a reduction in suppression is evident between 60 and 70 dB p.e. SPL. Again, the tendency for suppression to increase with increases in level is seen at Δf = 0.5 (panel (c)) and 1 (panel (d)). Finally, in contrast to the

level-dependence seen at other Δf, panel (e) shows suppression at $\Delta f = 2$ exhibited a small decrease with increasing tone burst level.

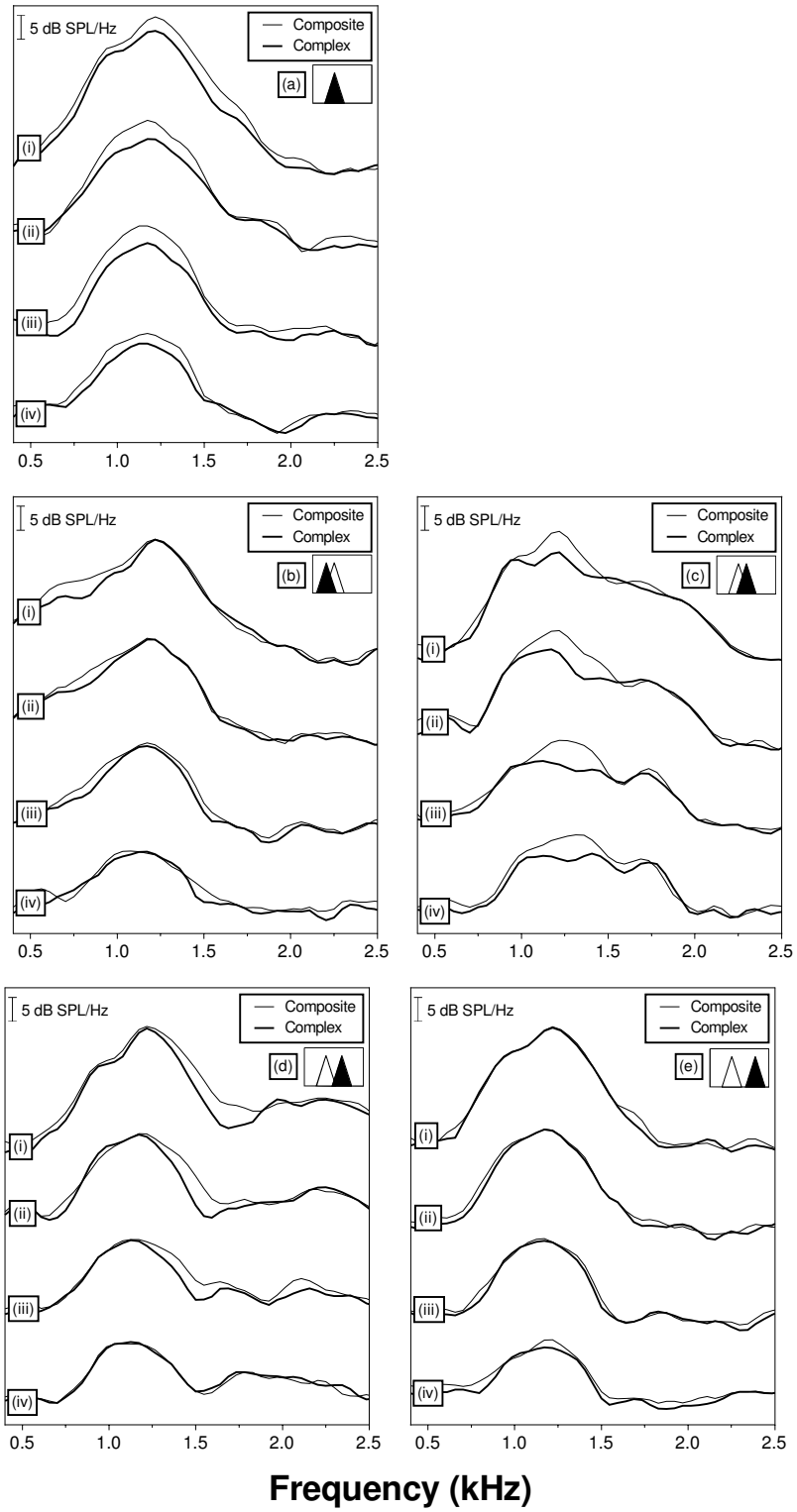

Figure 6. Mean composite (fine line) and complex (bold line) spectra obtained at Δf = (a) −0.5, (b) 0, (c) 0.5, (d) 1 and (e) 2. Each panel shows spectra at (i) 70, (ii) 60, (iii) 50 and (iv) 40 dB p.e. SPL. The inset in each panel is the same format as that described for Figure 1. Spectra are offset on the *y* axis for clarity and the scale bar represents 5 dB SPL/Hz.

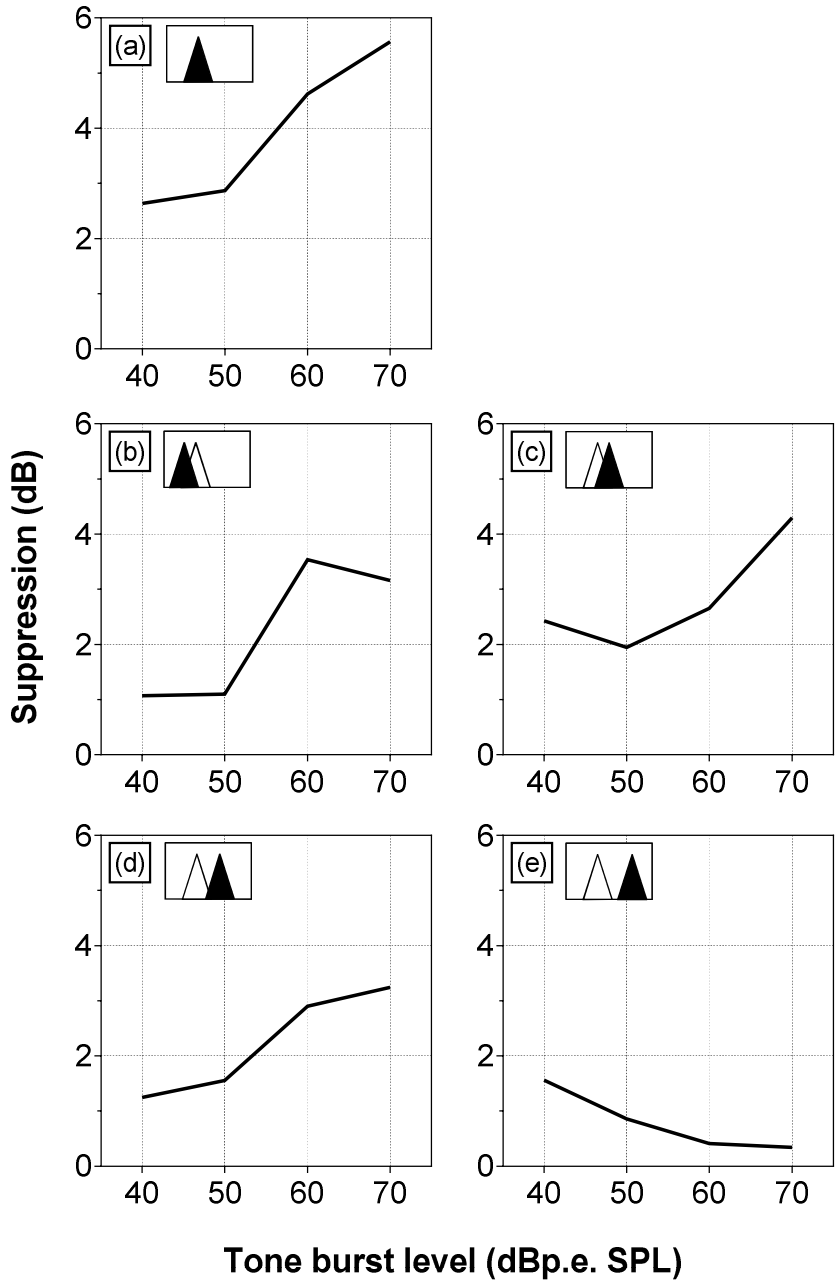

Figure 7. Suppression-level functions obtained at Δf = (a) 0, (b) −0.5, (c) 0.5, (d) 1 and (e) 2 for a representative ear. The inset in each panel is the same format as that described for Figure 1.

The mean suppression-level functions are shown in Fig. 8 (a) through (e). The dashed horizontal lines at approximately 1.1 dB represent the suppression threshold estimated across all ears. In the main, the mean suppression-level functions are similar to those shown for the

individual ear in Fig. 7, with the dominant pattern being increasing suppression with increases in tone burst level. This is in keeping with the only previously reported data for pairs of tone bursts reported by Yoshikawa et al. (2000), which showed an increase in suppression for a limited range of tone burst levels. The present suppression data is also in keeping with those obtained using combinations of three tone bursts (Xu et al., 1994; Killan and Kapadia, 2006). In both of these investigations suppression was shown to increase as a function of increasing tone burst level, up to a level of approximately 70 dB p.e. SPL.

Inspection of panels (a) and (c) reveals near-identical patterns of level-dependence at $\Delta f = 0$ and $\Delta f = 0.5$ respectively, broadly consistent with the predictions of the LNI-based model. In contrast, at $\Delta f = -0.5$ (panel (b)) and 1 (panel (d)), whilst the suppression-level functions show a progressive increase in suppression with tone burst level between 40 and 60 dB p.e. SPL, a further increase to 70 dB p.e. SPL caused a small reduction, or levelling-out in mean suppression. This is at odds with the predictions of the LNI-based model. A similar behaviour has been reported for the three tone burst suppression data by Killan and Kapadia (2006), at tone bursts levels above 75 dB p.e. SPL. They argued this behaviour resulted from contamination of the TBOAE response by long lasting stimulus ringing. Because such ringing components are essentially linear, they would not be expected to exhibit suppression. However, in the present experiment, levelling-out of suppression occurred at lower tone burst levels, at which recordings made in a 2 cm^3 passive cavity confirmed the absence of linear stimulus ringing.

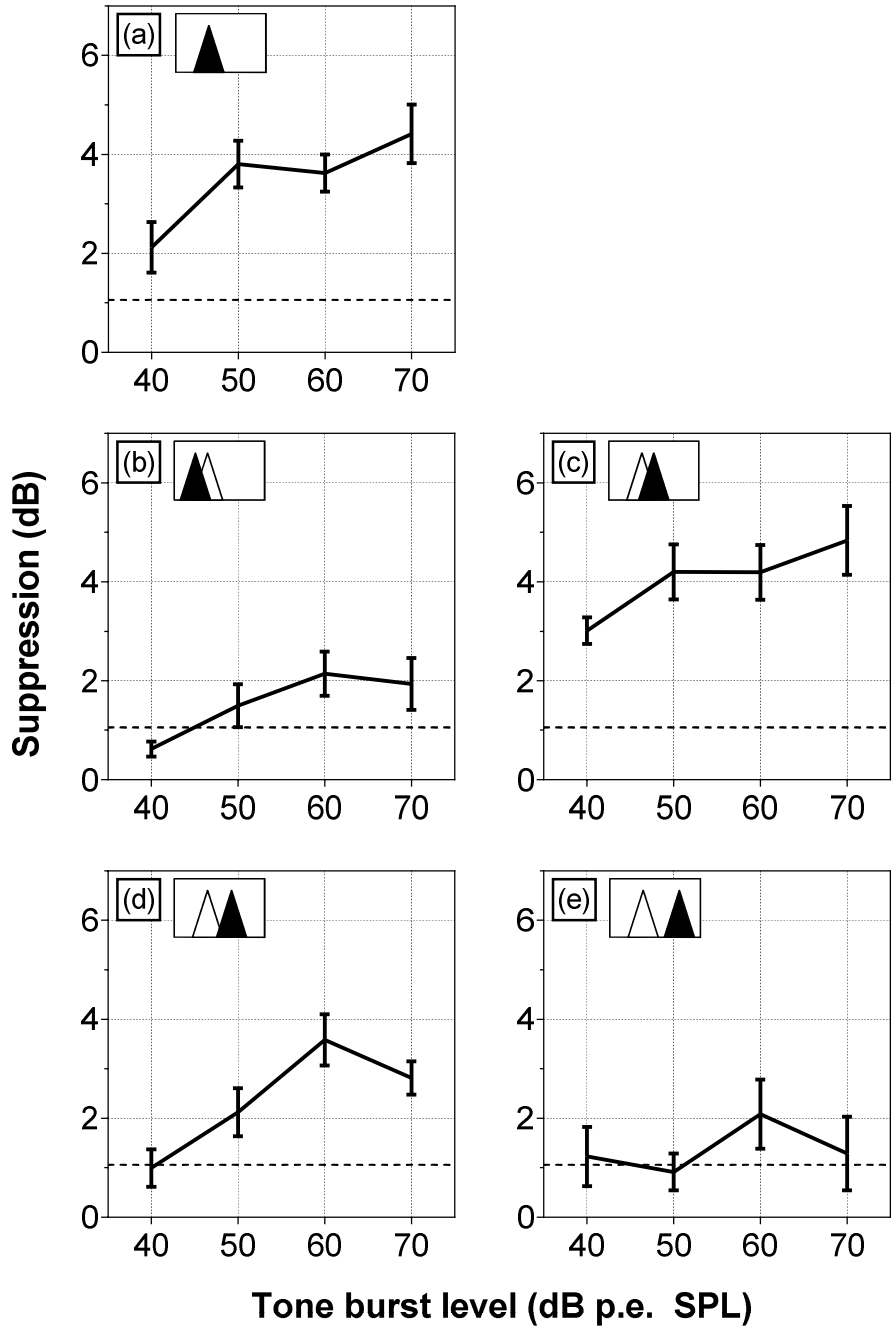

Figure 8. Mean suppression-level functions (n = 6) obtained at Δf = (a) 0, (b) −0.5, (c) 0.5, (d) 1 and (e) 2. Error bars represent ±1 SE of the mean. The dashed horizontal line represents the suppression threshold. The inset in each panel is the same format as that described for Figure 1.

An alternative explanation is that simultaneous suppression of TBOAEs more closely reflects the nonlinearity of the BM response (as opposed to the amplitude nonlinearity of TBOAEs).

Unlike TBOAE amplitude nonlinearity which becomes progressively more nonlinear with increasing stimulus level, the BM response is compressive at moderate stimulus levels but near-linear at higher levels (e.g. Kim et al., 1980; Cooper and Yates, 1994; Ren, 2002; Gorga et al., 2007). A similar argument has been used to account for a similar pattern of level-dependence reported for suppression of a CEOAE caused by an additional click separated in time (Kapadia and Lutman, 2000). However, the level at which the BM response returns to near-linearity (typically in the region of 80 dB SL (e.g. Ruggero et al., 1997)) is notably higher than the tone burst levels at which suppression was observed to level-out or roll-off (i.e. 45 to 55 dB SL). Further, it is not clear why suppression at $\Delta f = -0.5$ and 1 is more closely linked to the BM response than suppression at $\Delta f = 0.5$. A third possibility is that the levelling-out in suppression reflects a corresponding levelling-out in TBOAE amplitude nonlinearity at higher levels. Both the present data and previous reports indicate that whilst increases in TBOAE amplitude nonlinearity occur up to approximately 50 to 60 dB p.e. SPL, at higher levels the nonlinearity can remain reasonably constant (e.g. Epstein and Florentine, 2005). As was the case with an explanation based on BM response nonlinearity, however, it is not clear why such a pattern would not be observed at other values of Δf, especially $\Delta f = 0$ where suppression is a sole consequence of TBOAE amplitude nonlinearity.

The growth of suppression seen at $\Delta f = 1$ between 40 and 60 dB p.e. SPL is also notable. The increase of 2.6 dB was the largest across all values of Δf. The next largest growth was at $\Delta f = 0$ (1.7 dB), followed by $\Delta f = -0.5$ (1.5 dB) and $\Delta f = 0.5$ (1.2 dB). This is also at odds with the LNI-based model which predicts that the effect of tone burst level at $\Delta f = 1$ would be less pronounced than that seen at smaller values of Δf. Finally, panel (e) shows the results at $\Delta f = 2$ where at most tone burst levels, only minimal suppression was obtained. However, similar to the trend seen at $\Delta f = -0.5$ and 1 it is possible that an increase from 50 to 60 dB p.e. SPL

caused an increase in mean suppression, with a further increase to 70 dB p.e. SPL causing a reduction in suppression.

The observations made from Fig. 8 are confirmed by the results of statistical modelling. Tone burst level was added to the model as a categorical variable in order to incorporate the 'roll-off' effect seen at 70 dB p.e. SPL in the mean suppression-level functions. Its inclusion resulted in a highly significant reduction in model deviance ($\chi^2 = 29.08$, $df = 3$, $p < 0.001$), confirming tone burst level as having a substantial effect on suppression.[4] A significant increase in suppression for increases in tone burst level between 40 and 60 dB p.e. SPL ($t = 3.73$, $p < 0.001$) was also estimated, with a small, non-significant reduction in suppression for a further increase in tone burst level to 70 dB p.e. SPL ($t = 0.23$, $p = 0.43$). Finally, a non-significant interaction between Δf and tone burst level was obtained ($\chi^2 = 13.27$, $df = 12$, $p = 0.35$).

[4] As was the case in Experiment I, prior to testing the main explanatory variable, subjects' sex ($\chi^2 = 0.36$, $df = 1$, $p = 0.55$), age ($\chi^2 = 2.20$, $df = 1$, $p = 0.14$), mean hearing threshold level ($\chi^2 = 1.40$, $df = 1$, $p = 0.24$) and ear ($\chi^2 = 0.36$, $df = 1$, $p = 0.55$) were shown to be non-significant.

4. OVERALL DISCUSSION

The aim of the work described in this paper was to investigate the extent to which the simple LNI-based model previously outlined by Killan et al. (2012) is able to account for simultaneous suppression of TBOAEs. Specifically, two hypotheses, derived from the predictions of the model were tested. Experiment I aimed to test the extent to which a relationship between suppression magnitude and TBOAE amplitude nonlinearity (as a measure of TEOAE generator channel nonlinearity) existed in TBOAE data recorded from normal human ears. Experiment II set out to test a further hypothesis that the magnitude of simultaneous suppression of TBOAEs increases progressively as a function of tone burst level. The results of both experiments show that, whilst TBOAE data measured from human ears showed agreement with the model predictions at the majority of Δf, and as such provide support for the LNI-based mechanism being primarily responsible for suppression at these Δf, some findings were at odds with the predictions of the LNI-based model. In summary, the findings from Experiment I demonstrated a lack of a relationship between suppression measured at $\Delta f = 1$ and TBOAE amplitude nonlinearity. Experiment II showed that suppression measured at $\Delta f = -0.5$ and 1 (and possibly $\Delta f = 2$) exhibited an unexpected pattern of level-dependence, where suppression magnitude was observed to level-out at the highest tone burst level used. It is therefore reasoned that the LNI-based mechanism is not primarily responsible for suppression measured under these conditions, and an alternative explanation is required (or the LNI-based model is too simple).

Given the existence of basal-reflection components in the TEOAE response (Goodman et al., 2011; Moleti et al., 2012; Sisto et al., 2013), an alternative explanation of the findings at $\Delta f =$

1 (i.e. when TB_1 and TB_2 are 1 and 2 kHz respectively), is that simultaneous suppression is governed by a combination of the LNI-based mechanism and a mechanism underpinned by basal-reflection components. Basal-reflection components have shorter latencies than components generated at their characteristic place due to having a shorter round-trip travel time and having gone through fewer phase rotations. As a consequence basal-reflection components are at risk of being removed by the 8 ms onset time-window applied in both experiments. However, data reported by Goodman et al. (2009) show response components at 1 kHz, that are assumed to arise via basal-reflection, have latencies as long as approximately 10 ms for stimulus levels between 60 and 70 dB p.e. SPL. Similarly, Notaro et al. (2007) report possible 1 kHz basal-source components at latencies as long as 12 ms. It is therefore possible that, despite the use of relatively late time-windowing, basal-reflection components were able to contribute to the suppression measured in the present experiments. Based on data showing that basal-reflection components dominate at higher stimulus levels (Withnell et al., 2008; Goodman et al., 2011; Moleti et al., 2012; Sisto et al., 2013), it is suggested the LNI-based mechanism dominates at lower stimulus levels, with the basal-reflection suppression becoming more dominant as tone burst level increases. This combined explanation is able to account for the findings of Experiment I where there was no relationship evident between suppression and TBOAE amplitude nonlinearity, despite substantial suppression being measured. At 60 dB p.e. SPL it is likely that suppression was caused predominantly by the 2 kHz tone burst interfering with the generation of components (with frequencies in the region of 1 kHz) at the 2 kHz characteristic place. Because basal-reflection components show near-linear amplitude growth (Goodman et al., 2011; Sisto et al., 2013), it is unlikely that suppression will be linked to the compressive growth of TBOAE amplitude nonlinearity. It is also possible that the fast growth of suppression seen with increasing tone burst level at $\Delta f = 1$ described in Experiment II results from the increasing

contribution of the basal-reflection suppression mechanism to the total suppression measured (i.e. in addition to suppression governed by the LNI-based mechanism). Further, the levelling-out of suppression at 70 dB p.e. SPL could be explained as a reflection of a complete shift from the LNI-based mechanism to the basal-reflection suppression mechanism.

The findings of Experiment II at $\Delta f = -0.5$, where TB_2 had a lower frequency than TB_1 and therefore excited a BM region apical to the place tuned to 1 kHz, are harder to explain. The same argument used to explain unexpected results from experiment I might also apply here. That is, because higher frequency stimuli tend to be more effective suppressors than lower frequency stimuli (e.g. Brass and Kemp, 1993; Cooper and Rhode, 1996; Rhode and Recio, 2000; Yoshikawa et al., 2000; Killan and Kapadia, 2006; Keefe et al., 2008), the majority of suppression measured when $\Delta f = -0.5$ was in fact suppression of the response to TB_2 caused by TB_1. Thus it is possible that suppression was caused by the 1 kHz tone burst interfering with frequency components at 0.5 kHz generated at the BM region tuned to 1 kHz.

The experiments described in this paper did not allow testing of any alternative explanations for the suppression behaviours described, and as such any suggestions made are speculative. To better understand this simultaneous suppression phenomenon further investigations of this simultaneous suppression phenomenon are warranted, using more sophisticated modelling approaches (e.g. Verhulst et al., 2012), recording techniques that allow the early portions of the TBOAE response waveform to be preserved (e.g Keefe, 1998) and analysis techniques that decompose the TBOAE response in to components based on their likely origin (e.g. Jedrzejczak et al., 2004; Notaro et al., 2007). Such investigations are warranted given the implications that the conclusion of a combined suppression mechanism, and therefore

TBOAE generation mechanism, has for the diagnostic use of TBOAEs in the clinical setting. A number of clinical applications of TBOAEs (Epstein and Florentine, 2005; Jedrzejczak et al., 2012) are reliant on an assumed frequency- and place-specificity, i.e. a stimulus component at frequency *f* evokes response components at *f* from the BM place tuned to *f*. Whilst this can be assumed where TBOAEs arise via a local generation mechanism, it cannot be assumed where TBOAEs are basal-reflection components. Based on the results of the present experiments, it is suggested that for diagnostic uses of TBOAEs (where frequency- and place-specificity are considered desirable), tone bursts presented using linear averaging at low to moderate levels (i.e. less than 60 dB p.e. SPL) should be used.

REFERENCES

Ashmore, J., Avan, P., Brownell, W., Dallos, P., Dierkes, K., Fettiplace, R., Grosh, K., Hackney, C., Hudspeth, A., Jülicher, F. 2010. The remarkable cochlear amplifier. Hear. Res. 266, 1-17.

Brass, D., Kemp, D.T. 1993. Suppression of stimulus frequency otoacoustic emissions. J. Acoust. Soc. Am. 93, 920-939.

Carvalho, S., Büki, B., Bonfils, P., Avan, P. 2003. Effect of click intensity on click-evoked otoacoustic emission waveforms: Implications for the origin of emissions. Hear. Res. 175, 215-225.

Cooper, N., Rhode, W. 1996. Two-tone suppression in apical cochlear mechanics. Aud. Neurosci. 3, 123-134.

Cooper, N., Yates, G. 1994. Nonlinear input-output functions derived from the responses of guinea-pig cochlear nerve fibres: variations with characteristic frequency. Hear. Res. 78, 221-234.

Elberling, C., Parbo, J., Johnsen, N., Bagi, P. 1985. Evoked acoustic emission: clinical application. Acta oto-laryngologica 99, 77-85.

Epstein, M., Florentine, M. 2005. Inferring basilar-membrane motion from tone-burst otoacoustic emissions and psychoacoustic measurements. J. Acoust. Soc. Am. 117, 263-274.

Gilthorpe, M.S., Griffiths, G.S., Maddick, I.H., Zamzuri, A.T. 2000. The application of multilevel modelling to periodontal research data. Community Dental Health 17, 227-235.

Goldstein, H. 1986. Multilevel mixed linear-model analysis using iterative generalized least-sqaures. Biometrika 73, 43-56.

Goldstein, H. 2011. Multilevel statistical models. Chichester: Wiley.

Goodman, S.S., Fitzpatrick, D.F., Ellison, J.C., Jesteadt, W., Keefe, D.H. 2009. High-frequency click-evoked otoacoustic emissions and behavioral thresholds in humans. J. Acoust. Soc. Am. 125, 1014-1032.

Goodman, S.S., Mertes, I.B., Scheperle, R.A. 2011. Delays and growth rates of multiple TEOAE components, AIP Conference Proceedings, Vol. 1403. pp. 279-285.

Gorga, M.P., Neely, S.T., Dierking, D.M., Kopun, J., Jolkowski, K., Groenenboom, K., Tan, H., Stiegemann, B. 2007. Low frequency and high-frequency cochlear nonlinearity in humans. J. Acoust. Soc. Am. 122, 1671-1680.

Harte, J.M., Elliott, S.J., Kapadia, S., Lutman, M.E. 2005. Dynamic nonlinear cochlear model predictions of click-evoked otoacoustic emission suppression. Hear. Res. 207, 99-109.

Jedrzejczak, W.W., Blinowska, K.J., Konopka, W., Grzanka, A., Durka, P.J. 2004. Identification of otoacoustic emissions components by means of adaptive approximations. J. Acoust. Soc. Am. 115, 2148-2158.

Jedrzejczak, W.W., Kochanek, K., Trzaskowski, B., Pilka, E., Skarzynski, P.H., Skarzynski, H. 2012. Tone-burst and click-evoked otoacoustic emissions in subjects with hearing loss above 0.25, 0.5, and 1 kHz. Ear Hear. 33, 757-767.

Johnsen, N.J., Elberling, C. 1982. Evoked acoustic emissions from the human ear. 2. Normative data in young-adults and influence of posture. Scand. Audiol. 11, 69-77.

Kalluri, R., Shera, C.A. 2007. Near equivalence of human click-evoked and stimulus-frequency otoacoustic emissions. J. Acoust. Soc. Am. 121, 2097-2110.

Kapadia, S., Lutman, M.E. 2000. Nonlinear temporal interactions in click-evoked otoacoustic emissions. II. Experimental data. Hear. Res. 146, 101-120.

Kapadia, S., Lutman, M.E. 2001. Static input-output non-linearity as the source of non-linear effects in maximum length sequence click-evoked OAEs. Bri. J. Audiol. 35, 103-112.

Keefe, D.H. 1998. Double-evoked otoacoustic emissions. I. Measurement theory and nonlinear coherence. J. Acoust. Soc. Am. 103, 3489-3498.

Keefe, D.H., Ellison, J.C., Fitzpatrick, D.F., Gorga, M.P. 2008. Two-tone suppression of stimulus frequency otoacoustic emissions. J. Acoust. Soc. Am. 123, 1479-1494.

Kemp, D., Chum, R. 1980. Properties of the generator of stimulated acoustic emissions. Hear, Res. 2, 213-232.

Killan, E.C., Kapadia, S. 2006. Simultaneous suppression of tone burst-evoked otoacoustic emissions–Effect of level and presentation paradigm. Hear. Res. 212, 65-73.

Killan, E.C., Lutman, M.E., Montelpare, W.J., Thyer, N.J. 2012. A mechanism for simultaneous suppression of tone burst-evoked otoacoustic emissions. Hear. Res. 285, 58-64.

Kim, D., Molnar, C., Matthews, J. 1980. Cochlear mechanics: Nonlinear behavior in two-tone responses as reflected in cochlear-nerve-fiber responses and in ear-canal sound pressure. J. Acoust. Soc. Am. 67, 1704-1721.

Kulawiec, J.T., Orlando, M.S. 1995. The contribution of spontaneous otoacoustic emissions to the click evoked otoacoustic emissions. Ear Hear. 16, 515-520.

Lineton, B., Thornton, A., Baker, V. 2006. An investigation into the relationship between input–output nonlinearities and rate-induced nonlinearities of click-evoked otoacoustic emissions recorded using maximum length sequences. Hear. Res. 219, 24-35.

Moleti, A., Al-Maamury, A.M., Bertaccini, D., Botti, T., Sisto, R. 2013. Generation place of the long- and short-latency components of transient-evoked otoacoustic emissions in a nonlinear cochlear model. J. Acoust. Soc. Am. 133, 4098-4108.

Moleti, A., Botti, T., Sisto, R. 2012. Transient-evoked otoacoustic emission generators in a nonlinear cochlea. J. Acoust. Soc. Am. 131, 2891-2903.

Norton, S.J., Neely, S.T. 1987. Tone-burst-evoked otoacoustic emissions from normal-hearing subjects. J. Acoust. Soc. Am. 81, 1860-1872.

Notaro, G., Al-Maamury, A.M., Moleti, A., Sisto, R. 2007. Wavelet and matching pursuit estimates of the transient-evoked otoacoustic emission latency. J. Acoust. Soc. Am. 122, 3576-3585.

Nuttall, A.L., Dolan, D.F. 1996. Steady-state sinusoidal velocity responses of the basilar membrane in guinea pig. J. Acoust. Soc. Am. 99, 1556-1565.

Patuzzi, R. 1996. Cochlear micromechanics and macromechanics. In: Dallos, P., Popper, A.N. & Fay, R.R. (eds) The Cochlea, New York, Springer-Verlag: 186-257.

Prieve, B.A., Gorga, M.P., Neely, S.T. 1996. Click-and tone-burst-evoked otoacoustic emissions in normal-hearing and hearing-impaired ears. J. Acoust. Soc. Am. 99, 3077-3086.

Probst, R., Coats, A., Martin, G., Lonsbury-Martin, B. 1986. Spontaneous, click-, and toneburst-evoked otoacoustic emissions from normal ears. Hear. Res. 21, 261-275.

Probst, R., Lonsbury-Martin, B.L., Martin, G.K. 1991. A review of otoacoustic emissions. J. Acoust. Soc. Am. 89, 2027-2067.

Ren, T.Y. 2002. Longitudinal pattern of basilar membrane vibration in the sensitive cochlea. P. Natl. Acad. Sci. USA 99, 17101-17106.

Rhode, W.S., Recio, A. 2000. Study of mechanical motions in the basal region of the chinchilla cochlea. J. Acoust. Soc. Am. 107, 3317-3332.

Robinette, M., Glattke, T. (eds) 2007. Otoacoustic emissions: clinical applications. New York: Thieme.

Ruggero, M.A., Rich, N.C., Recio, A., Narayan, S.S., Robles, L. 1997. Basilar-membrane responses to tones at the base of the chinchilla cochlea. J. Acoust. Soc. Am. 101, 2151-2163.

Rutten, W. 1980. Evoked acoustic emissions from within normal and abnormal human ears: comparison with audiometric and electrocochleographic findings. Hear. Res. 2, 263-271.

Shera, C.A. 2004. Mechanisms of mammalian otoacoustic emission and their implications for the clinical utility of otoacoustic emissions. Ear Hear. 25, 86-97.

Sisto, R., Moleti, A. 2007. Transient evoked otoacoustic emission latency and cochlear tuning at different stimulus levels. J. Acoust. Soc. Am. 122, 2183-2190.

Sisto, R., Moleti, A. 2008. Transient evoked otoacoustic emission input/output function and cochlear reflectivity: Experiment and model. J. Acoust. Soc. Am. 124, 2995-3008.

Sisto, R., Sanjust, F., Moleti, A. 2013. Input/output functions of different-latency components of transient-evoked and stimulus-frequency otoacoustic emissions. J. Acoust. Soc. Am. 133, 2240-53.

Snijders, T.A.A., Bosker, R.J. 2011. Multilevel analysis: An introduction to basic and advanced multilevel modeling. London: Sage Publications Limited.

Tavartkiladze, G., Frolenkov, G., Kruglov, A., Artamasov, S. 1994. Ipsilateral suppression effects on transient evoked otoacoustic emission. Bri. J. Audiol. 28, 193-204.

Thornton, A., Lineton, B., Baker, V., Slaven, A. 2006. Nonlinear properties of otoacoustic emissions in normal and impaired hearing. Hear. Res. 219, 56-65.

Verhulst, S., Dau, T., Shera, C.A. 2012. Nonlinear time-domain cochlear model for transient stimulation and human otoacoustic emission. J. Acoust. Soc. Am. 132, 3842-3848.

Withnell, R.H., Hazlewood, C., Knowlton, A. 2008. Reconciling the origin of the transient evoked ototacoustic emission in humans. J. Acoust. Soc. Am. 123, 212-221.

Withnell, R.H., McKinley, S. 2005. Delay dependence for the origin of the nonlinear derived transient evoked otoacoustic emission. J. Acoust. Soc. Am. 117, 281-291.

Xu, L., Probst, R., Harris, F.P., Roede, J. 1994. Peripheral analysis of frequency in human ears revealed by tone burst evoked otoacoustic emissions. Hear. Res. 74, 173-180.

Yates, G.K., Withnell, R.H. 1999. The role of intermodulation distortion in transient-evoked otoacoustic emissions. Hear. Res. 136, 49-64.

Yoshikawa, H., Smurzynski, J., Probst, R. 2000. Suppression of tone burst evoked otoacoustic emissions in relation to frequency separation. Hear. Res. 148, 95-106.

Zettner, E.M., Folsom, R.C. 2003. Transient emission suppression tuning curve attributes in relation to psychoacoustic threshold. J. Acoust. Soc. Am. 113, 2031-2041.