Evaluating auditory brainstem responses to different chirp stimuli at three levels of stimulation

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Auditory brainstem responses (ABRs) are recorded in ten normal-hearing adults (20 ears) in response to a standard 100 μ s click and five chirps having different durations (sweeping rates). The chirps are constructed from five versions of a power function model of the cochlear-neural delay that is based on derived-band ABR latencies from $N=81$ normal-hearing adults [Elberling, C., and Don, M. (2008). *J. Acoust. Soc. Am.* **124**, 3022–3037]. The click and the chirps have identical amplitude spectra and, in general, for each of the three stimulus levels 60, 40, and 20 dB nHL, the ABRs to the chirps are significantly larger than the ABRs to the click. However, the shorter chirps are the most efficient at higher levels of stimulation whereas the longer chirps are the most efficient at lower levels. It is suggested that two different mechanisms are responsible for these observed changes with stimulus level—(1) upward spread of excitation at higher levels, and (2) an increased change of the cochlear-neural delay with frequency at lower levels.

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I. INTRODUCTION

A. The chirp stimulus

An upward chirp attempts to compensate for the temporal dispersion in the cochlea, which partly is caused by the traveling wave, e.g., Shore and Nuttall, 1985; Lütkenhöner *et al.*, 1990; Dau *et al.*, 2000. The traveling wave which is set up by a transient stimulus—as, for example, a click—is delayed from the base of the cochlea to its apical end. Therefore, the neural elements along the cochlear partition are not excited at the same time. At each location, the resulting delay is mainly caused by the cochlear traveling wave, and consists of a level-independent delay (as measured by von Békésy, 1960), a level-dependent delay (associated with the filter build-up time of the basilar membrane - hair cell transducer), and a constant delay in the hair cell synapse. These delay components are discussed in, e.g., Eggermont, 1979; Dau *et al.*, 2000; Ruggero and Temchin, 2007; Elberling and Don, 2008. Thus, the summed output from the different neural elements gets temporally smeared, and this in turn reduces the amplitude of the compound neural response. This temporal smearing, or reduced synchrony, can partly be compensated for by a brief stimulus, in which the higher frequencies are delayed relative to the lower frequencies, i.e., an upward chirp. The internal spectral timing of such a chirp must be designed using a model of the cochlear-neural delay¹ as reflected by the transient response of the auditory periphery. A

chirp stimulus was first applied in auditory electrophysiology by Shore and Nuttall (1985), and since that published report, fundamental characteristics of the chirp and its use within the auditory field have been evaluated and reported in the literature. In several publications it has been demonstrated that an upward chirp is more efficient than a click when recording the auditory compound action potential (ACAP), the auditory brain stem response (ABR), or the auditory steady-state response (ASSR), for a review see, e.g., Elberling *et al.*, 2007; Elberling and Don, 2008.

B. Recent findings

Several attempts have been made to find a chirp that most efficiently evokes ABRs in humans, and different delay models have therefore been examined. Models based on: (1) frequency-specific ABR latencies were applied by Lütkenhöner *et al.* (1990), Fobel and Dau (2004), and Elberling *et al.* (2007), (2) a cochlear linear delay-line by Dau *et al.* (2000), Fobel and Dau (2004), Stürzebecher *et al.* (2006), and Elberling *et al.* (2007), (3) stimulus-frequency otoacoustic emission latencies by Fobel and Dau (2004), and (4) derived-band ABR latencies by Elberling *et al.* (2007) and Elberling and Don (2008).

Fobel and Dau (2004) carried out a comparative study with chirps based on (1) frequency-specific ABR latencies by Neely *et al.* (1988)—the *A-chirp*, (2) a linear cochlear model by de Boer (1980)—the *M-chirp*, and (3) stimulus-frequency otoacoustic emission latencies by Shera and Guinan (2000)—the *O-chirp*. While all chirps evoked larger ABRs than the click, only small differences were found between the

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amplitudes of ABRs evoked by the M-chirp and the O-chirp at low and medium stimulus levels. However, the A-chirp produced the largest ABR amplitudes particularly at low stimulus levels.

Whereas the waveform of the M-chirp and the O-chirp were independent of stimulus level, the waveform of the A-chirp changed systematically with level, because the underlying ABR-latency model (Neely *et al.*, 1988) indicates a relatively small change in latency with frequency at high levels and a larger change at low levels. Therefore, for the recording of ABRs in normal-hearing subjects, the findings by Fobel and Dau (2004) seem to imply that a chirp, which becomes progressively longer the lower the stimulus level, could be more efficient than a chirp, having a level-independent waveform.

Elberling *et al.* (2007) introduced a preliminary cochlear-neural delay model based on the derived-band ABR latencies recorded in $N=42$ normal-hearing subjects (Don *et al.*, 1998). From this model a chirp was constructed—the *Don chirp*, which was compared with a chirp based on a linear cochlear model (de Boer, 1980)—the *de Boer chirp*, and a chirp based on tone-burst ABR latencies (Neely *et al.*, 1988)—the *Neely et al. chirp*.² ASSRs were recorded from $N=49$ young, normal-hearing subjects in response to a click and the three chirps at 50 and 30 dB nHL. All chirps generated larger ASSRs than the click, and at 50 dB nHL the Don chirp produced larger ASSRs than the two other chirps, whereas at 30 dB nHL no significant differences were found between the ASSRs from the three different chirps.

In a succeeding report (Elberling and Don, 2008), additional derived-band ABR latencies from $N=39$ normal-hearing subjects (Don *et al.*, 2005) were added to the cochlea-neural delay model, thereby allowing the final model to be based on latency data from $N=81$ subjects. The data set from each test subject was modeled by a power function, which was fitted to the individual data points:

$$\tau = k \cdot f^{-d}, \quad (1)$$

where τ is the latency in seconds, f is the frequency in Hertz, and k and d are constants. The latency-frequency function was used to model the cochlear-neural delay in the normal auditory periphery caused by the click stimulus. The $N=81$ paired values of k and d were presented by Elberling and Don, (2008) (Fig. 2), and are replotted here in Fig. 1. The figure shows the large variation between the data pairs, and corresponds to a change in latency (between 5700 and 710 Hz) ranging from 1.9 to 5.0 ms across the $N=81$ normal-hearing subjects. Because repeated measures of the derived-band latencies,³ as measured by Don *et al.* (2005), are obtained with a standard deviation of approximately 0.13 ms for the 5700 Hz derived band and 0.20 ms for the 710 Hz derived band, most of the observed variation between the data pairs in Fig. 1 reflects a true interindividual variation.

Elberling and Don (2008) also revisited the data published by Don *et al.* (1998), describing derived-band ABR latencies as a function of stimulus level. The re-examination of the data found a significant change in the latency difference between the 5700 Hz and the 1400 Hz derived bands at the lowest levels of stimulation (10–20 dB nHL). At low

FIG. 1. Distribution of the paired parameter values, k and d , which define the latency-frequency function [Eq. (1)]. The individual paired values are obtained from derived-band ABRs in $N=81$ normal-hearing subjects, as described by Elberling and Don (2008). The chosen locations of five pairs (k, d) are indicated on the graph, and their numerical values given in the table to the right. The models, corresponding to the five parameter pairs, are used to construct five different chirps: Chirp 1, 2, 3, 4, and 5 (see text for further details).

levels, unfortunately, the available amount of data was insufficient for a reliable estimate of the 710 Hz derived-band ABR latency. Thus, the 1400 Hz derived band was the lowest derived band that could be used for this analysis. The re-examination indicated a larger change in latency with frequency (here between 5700 and 1400 Hz) at lower stimulus levels compared to the change at high levels. However, because the observed difference between high and low levels of the changes in latency with frequency was only about 0.55 ms, it was concluded that stimulus level didn't seem to have any major effect on the relative cochlear-neural delay. Therefore, the final delay model was believed to be valid over a wide range of stimulus levels.

In the study by Elberling and Don (2008) click and chirp ABRs were recorded at two levels: 60 and 50 dB nHL. Contrary to the click, it was found that the chirp produced smaller ABRs at 60 dB nHL than at 50 dB nHL, and this reduced efficiency of the chirp at higher levels of stimulation was suggested to be due to upward spread of excitation. Their arguments for this suggestion were as follows: At lower stimulation levels each frequency component of the chirp excites a restricted area of the cochlea, but at higher levels the excitation spreads—especially due to upward spread of excitation. Each frequency component of the chirp arrives in the cochlea with a given timing, dependent on the latency-frequency model used for the chirp design. At higher levels each location will thus be excited by a broader range of frequency components each arriving at a different point in time. This will lead to a desynchronization of the neural excitation resulting in reduced response amplitude, and the longer the chirp the larger the desynchronization. Therefore, there might be an upper level of stimulation beyond which the chirp no longer will be more efficient than the click. See also the discussion by Dau (2003).

C. The aims of the present study

Based on the findings presented above there are three specific aims of the present study.

First, we want to confirm the implication of the findings by [Fobel and Dau \(2004\)](#) that the most efficient chirp is a chirp that becomes progressively longer the lower the level of stimulation. This investigation is carried out using five different chirps that are designed by systematically changing the parameters of the cochlear-neural delay model by [Elberling and Don \(2008\)](#). It is hypothesized that as presentation level is reduced, the largest ABR amplitude will occur for longer chirps. Due to the specific way the latencies are referenced and the stimuli are located temporally (described below), it is also hypothesized that, the latency of the ABR decreases the longer and the more intense the chirp.

Second, we want to discuss and evaluate whether the most efficient chirp is in accordance with the slightly larger change in latency with frequency at low levels as found by [Elberling and Don \(2008\)](#). The model parameters of the most efficient chirp at low levels are compared with the larger change in latency with frequency found by the re-examination of the derived-band ABR latencies described above. Based on the explanation in Sec. I B, about upward spread of excitation, it is hypothesized that with increasing level, we will observe a tendency of the ABR amplitude to decrease for longer chirps whereas for the click and shorter chirps, the ABR amplitude will increase with level. Moreover, it is hypothesized that the amount of change of the ABR latency as a function of level is greatest for the longer chirps.

Third, we want to discuss the efficiency of the different chirps at medium to higher levels of stimulation. We hypothesize that it is likely that upward spread of excitation limits the efficiency of the chirp at higher stimulus levels and accounts for the observed amplitude and latency changes.

II. METHOD

A. Subjects

The test group consists of ten normal-hearing subjects (four females and six males) whose ages range from 23 to 43 years. The pure-tone thresholds are equal to or better than 10 dB HL for the frequencies 500 to 4000 Hz and equal to or better than 15 dB HL for 6000 and 8000 Hz. Both ears are tested on all test subjects.

In accordance with the general rules of the Danish Central Ethical Committee and the Danish Medicines Agency, no written study approval is required as long as the experimental testing is part of a quality control procedure with CE-marked equipment,⁴ and the equipment is used as intended. Before the testing begins, the purpose of the study and details of the test procedure are explained to each test subject by the tester, who subsequently answers all questions the test subject has regarding the participation in the study. Finally, each test subject reads and signs an informed consent form.

B. Stimuli

The basis for our chirp design consists of the delay model mentioned above and described in more detail by [Elberling and Don \(2008\)](#). In order to embrace the large inter-individual variation in the underlying model data, chirps corresponding to five different delay models are constructed.

FIG. 2. The cochlear-neural delay models (delay as a function of frequency) used to generate the five chirps, in accordance with the parameter values in Fig. 1. The final delay models are all vertically offset to provide a zero delay at 10 000 Hz. For each model the chirp number and the corresponding changes of the delay between 5700 and 710 Hz are indicated. For completeness, the model for the click is also indicated. The broken lines marked N_{60} , N_{40} , and N_{20} indicate the delay models by [Neely et al. \(1988\)](#) at 60, 40, and 20 dB nHL [corresponding to 85, 65, and 45 SPL in the original labeling by [Neely et al. \(1988\)](#)].

The five models—resulting in Chirp 1, 2, 3, 4, and 5—are indicated in Fig. 1, together with the corresponding paired k and d values, which are evenly distributed between the two end points of the distribution of the data obtained from the $N=81$ normal-hearing individuals. The model corresponding to Chirp 3 uses the mean values of k and d and approximates therefore the chirp that was designed and used by [Elberling and Don \(2008\)](#).

Before the model data is used, each power function is offset to have zero delay at 10 000 Hz. The final model functions are shown in Fig. 2, together with the changes of the delay with frequency (between 5700 and 710 Hz) for each of the five chirps and a standard 100 μ s click, which uses a constant model delay of zero. All six stimuli are generated using the frequency domain method ([Elberling et al., 2007](#), [Elberling and Don, 2008](#)), within a frequency band from 200 Hz to 10 000 Hz (the first spectral null of the 100 μ s click), and with identical amplitude spectra and spectrum levels. Via the five model functions the temporal courses of the chirps are linked to the frequency axis. Thus, for all chirps the 0 ms reference corresponds to 10 000 Hz. The final stimuli and their relative timing are shown in Fig. 3.

The stimuli are presented at a rate of 27/s and delivered through a pair of ER-2 insert earphones. The presentation levels are 60, 40 and 20 dB nHL.⁵ Acoustic calibration is obtained by calibrating the click in accordance with [ISO 389-6 \(2007\)](#) in the occluded ear simulator, [IEC 60711 \(1981\)](#). Since each chirp is tailored to the click—by having identical amplitude spectra (and consequently identical spectrum levels)—all the chirps have the same hearing level as the click (see [Elberling et al. 2007](#), p. 2783).

C. ABR recording

The ABRs are recorded with Interacoustics Eclipse EP25 ABR system[®]. The test subjects are placed on a couch

FIG. 3. The graph shows the electrical waveform and its temporal location for the click and each of the five chirps. All six stimuli have identical amplitude spectra (and consequently identical spectrum levels). In this plot, however, the chirps are scaled $\times 2$ relative to the click.

in an ordinary, silent test room, which is neither sound treated nor electrically shielded. The electrophysiological signal is picked up differentially between two electrodes—one applied high on the midfrontal area (F_z) and the other on the ipsilateral mastoid (M_1 or M_2); an electrode at the lower midfrontal area (F_{pz}) serves as ground. The EEG is band pass filtered from 100 to 3000 Hz using filter slopes of 12 dB/octave. During the data acquisition a running estimate of the physiological background noise is made (Elberling and Don, 1984), and the ABRs are obtained by weighted averaging (Elberling and Wahlgreen, 1985; Don and Elberling, 1994). Weighted averaging reduces the destructive effects on the averaged waveform from spurious variations in the background noise by emphasizing the contribution from the sweeps having low background noise. The averaging is ter-

minated when the estimated residual background noise is 40 nV (rms) or less. Over all recordings across all test subjects the residual background noise is 39.4 nV, which on average is obtained after 2715 sweeps.

D. Data analysis

Each ABR recording is described by the characteristics of the most salient response peak⁶—wave V. The recordings are located on the time axis in such a way that the response time reference (0 ms) is the estimated time of arrival at the tympanic membrane of the acoustic stimuli (the click and the 10 000 Hz components of the chirps), taking the acoustical delay in the ER-2 sound tube into consideration; this corresponds to the 0 ms point on the stimulus time axis in Fig. 3. When the response peak is identified, the peak-to-trough amplitude and the peak latency are automatically measured from each recording. The data from each condition (level and stimulus) is checked for normality by means of the Kolmogorov–Smirnov test (Siegel, 1956), which indicates that none of the data sets deviate significantly from a Gaussian distribution. Therefore the amplitude and latency for each condition are described by the sample mean and standard deviation. Because the different data sets for each parameter (amplitude and latency) do not have the same variance in the different conditions, the nonparametric Wilcoxon matched-pair signed-rank test is used to analyze the paired data (Siegel, 1956). Bonferroni's correction for repeated testing (Hochberg and Tamhane, 1987) is applied.

III. RESULTS

For each condition (level and stimulus), the mean amplitudes, the mean latencies and the corresponding standard deviations are calculated and shown in Table I. The mean amplitudes $\pm$ the *standard errors*⁷ ($SE = SD/\sqrt{N}$, $N = 20$) are graphically displayed in Fig. 4, whereas the mean latencies $\pm$ the *standard deviations* are shown in Fig. 5.

TABLE I. Amplitude and latency (mean and standard deviation) of the ABRs recorded to the click and the five chirps at three stimulation levels. For the amplitude subtable, the lowest row shows the ratio (mean and standard deviation in %) of the difference in amplitude at 60 and 20 dB nHL to the amplitude at 20 dB nHL. For the latency subtable, the lowest row shows the latency difference (mean and standard deviation) between the ABR at 20 dB nHL and the ABR at 60 dB nHL.

Level	Click		Chirp 1		Chirp 2		Chirp 3		Chirp 4		Chirp 5	
dB nHL	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Amplitude p-p (nV)												
60	407	91	624	162	654	118	596	118	516	96	389	120
40	368	92	560	135	613	119	645	79	631	79	581	100
20	256	61	311	86	339	86	349	72	382	83	391	91
ΔA_{20-60} (%)	64	42	107	51	104	59	80	57	41	40	4	38
Latency (ms)												
60	5.88	0.25	4.97	0.28	4.57	0.35	4.12	0.51	3.50	0.51	2.87	0.38
40	6.59	0.44	6.15	0.29	5.96	0.23	5.76	0.27	5.48	0.34	4.98	0.59
20	7.60	0.49	7.23	0.36	7.12	0.32	6.97	0.34	6.86	0.36	6.66	0.36
ΔL_{20-60} (ms)	1.72	0.35	2.26	0.45	2.55	0.54	2.85	0.49	3.36	0.48	3.79	0.42

FIG. 4. The mean ABR amplitude ± 1 standard error (Table I) are plotted for each stimulus (Click, Chirp 1, 2, 3, 4, and 5), and level (60, 40, and 20 dB nHL). Each stimulus is located on the x-axis corresponding to the change of delay with frequency in the underlying model, as indicated in Fig. 2.

The mean amplitudes indicate that Chirp 2 generates the largest ABRs at 60 dB nHL, that Chirp 3 generates the largest ABRs at 40 dB nHL, and that Chirp 5 generates the largest ABRs at 20 dB nHL. The distribution of the mean latencies across the different stimuli demonstrates a significant level effect. At 60 dB nHL the difference is about 3 ms between the latencies to the click (5.88 ms) and Chirp 5 (2.87 ms), whereas at 20 dB nHL the difference is reduced to about 1 ms (click=7.60 ms and Chirp 5=6.66 ms). Another way of viewing these latency data is shown in the last row of the latency data in Table I. In this row, we observe that the differences in latency between 60 dB nHL and 20 dB nHL are larger for the chirps than for the click but also that the difference increases as the duration of the chirp becomes longer. That is, the largest difference occurs for Chirp 5. As

FIG. 5. The mean ABR latency ± 1 standard deviation (Table I) are plotted for each stimulus (Click, Chirp 1, 2, 3, 4, and 5), and level (60, 40, and 20 dB nHL). Each stimulus is located on the x-axis corresponding to the change of delay with frequency in the underlying model, as indicated in Fig. 2.

discussed later, all of these latency results support the hypothesis that it is the spread of excitation with level that limits the efficiency of the chirp.

Statistical analysis of the amplitude data by means of the Wilcoxon matched-pair signed-rank test is used to compare the distribution of amplitudes of the click responses to that of each of the five chirps, as well as the amplitudes of the largest chirp responses to those of the other stimuli. The results (mean amplitude ratios and level of significance) are shown in Table II, and can be described as follows:

At 60 dB nHL, Chirps 1, 2, 3, and 4 produce significantly higher response amplitudes than the click, and Chirp 2 produces significantly higher amplitudes than Chirp 4 and Chirp 5. Thus, the mean amplitude decreases significantly with increasing chirp duration (Chirp 2 $\Rightarrow$ Chirp 5; Fig. 4).

At 40 dB nHL, all chirps produce significantly higher response amplitudes than the click. According to our hypothesis, that for lower presentation levels the largest ABR amplitude will occur for longer chirps, we observe that the largest amplitude shifts to the longer Chirps 3 and 4 (Fig. 4).

At 20 dB nHL, all chirps produce significantly higher response amplitudes than the click, and consistent with our hypothesis, Chirp 5, the longest chirp, produces the highest amplitude and is significantly higher than Chirp 1 (Fig. 4). The trend of the amplitude distribution, however, indicates that the true maximum might be obtained with a chirp longer in duration than Chirp 5, which is the longest one used in the present study.

The ABRs show a large variability across ears—both in amplitude as reflected in the large standard deviations (Table I)—and in chirp efficiency. Figure 6 shows, for the three stimulus levels, the number of cases where each chirp has generated the largest response in the individual ears:

- At 60 dB nHL the largest response is obtained most often by Chirps 1 and 2.
- At 40 dB nHL the largest response is obtained more evenly from all chirps.
- At 20 dB nHL the largest response is obtained most often by Chirps 4 and 5.

However, it should be noted that the click does not generate the largest response in any of the 20 ears at any of the three levels of stimulation.

The three distributions (one for each level) across test subjects of the chirp (Chirp No. 1 $\Rightarrow$ 5) that generates the largest response, are compared by the Wilcoxon matched-pair signed-rank test. The results demonstrate that the three distributions differ significantly from each other (60–40: $p < 0.05$; 40–20: $p < 0.05$; 60–20: $p < 0.01$). Therefore, over the 60–20 dB nHL range, there is a systematic change in which chirps generate the largest ABRs: at 60 dB nHL the shortest chirps (the lowest numbers) are the most efficient, whereas at 20 dB nHL the longest chirps (the highest numbers) are now the most efficient.

In order to present the morphology of the ABR waveforms in response to different levels and stimulus types, grand average waveforms are computed as follows: First, each ABR is time shifted so the latency of the most salient response peak (wave V) coincides with the mean latency

TABLE II. The amplitude ratio between the ABRs recorded to the six stimuli at three stimulation levels. In the three subtables, the first row shows the amplitude ratio between the chirp ABRs and the click ABR, whereas the second row shows the amplitude ratio between the ABR of the chirp (which is indicated to the left in row two) and the ABRs to the other five stimuli. The corresponding levels of significance is indicated (NS =nonsignificant at the 5% level).

	Click	Chirp 1	Chirp 2	Chirp 3	Chirp 4	Chirp 5
60 dB nHL						
Click	...	1.57 $p < 0.01$	1.66 $p < 0.01$	1.55 $p < 0.01$	1.33 $p < 0.05$	1.01 NS
Chirp 2	1.66 $p < 0.01$	1.11 NS	...	1.13 NS	1.31 $p < 0.01$	1.88 $p < 0.01$
40 dB nHL						
Click	...	1.59 $p < 0.01$	1.76 $p < 0.01$	1.86 $p < 0.01$	1.84 $p < 0.01$	1.68 $p < 0.01$
Chirp 3	1.86 $p < 0.01$	1.21 NS	1.08 NS	...	1.03 NS	1.14 NS
20 dB nHL						
Click	...	1.22 $p < 0.01$	1.33 $p < 0.01$	1.40 $p < 0.01$	1.54 $p < 0.01$	1.59 $p < 0.01$
Chirp 5	1.59 $p < 0.01$	1.35 $p < 0.05$	1.22 NS	1.16 NS	1.04 NS	...

obtained at the actual condition (mean latency for each level and stimulus type, Table I). Next, the average across each set of the 20 time-adjusted ABRs is computed. The 18 ($=3 \times 6$) grand averages are shown in Fig. 7. Most of the grand average waveforms are relatively well defined and resolve two to three wave peaks. However at 60 dB nHL, the responses to Chirp 3, 4, and especially Chirp 5 have limited waveform resolution and, with the chosen recording window, the initial parts of the responses are concealed due to the negative latency shifts.

IV. DISCUSSION

Overall the results demonstrate that the efficiency of the individual five chirps changes with stimulus level, and confirm the original findings by [Fobel and Dau \(2004\)](#), that the most efficient chirp is a chirp which becomes progressively longer the lower the stimulus level. The changes with stimulus level we observe are probably caused by two different mechanisms—one at lower stimulus levels and another at higher levels.

FIG. 6. For the three levels (60, 40, and 20 dB nHL), the graph shows for each of the chirps (Chirp 1, 2, 3, 4, and 5), the number of cases with the largest ABR amplitude.

At 40 dB nHL, which is the medium level used here, Fig. 4 demonstrates that the largest mean ABR amplitude is generated by Chirp 3. However, the amplitude distribution is relatively flat, in agreement with both Fig. 6 and the wide distribution of the original derived-band latencies used to model the cochlear-neural delay (Fig. 1). Therefore, the mean values of the parameters (k, d) in the delay model appear to be adequate for the design of an efficient chirp (Chirp 3) to be used at 40 dB nHL.

At 20 dB nHL, the use of the mean parameter values (Chirp 3) does not lead to the most efficient chirp, and it appears that the use of a model with a larger change of the delay with frequency would be more adequate (corresponding to Chirp 4 and Chirp 5). As mentioned in the Introduction above, reanalysis of the original data by [Don et al. \(1998\)](#) indicated the latency difference between the 5700 and 1400 Hz derived bands to be about 0.5 ms longer at lower levels (10–20 dB nHL) than at 60 dB nHL ([Elberling and Don, 2008](#)). Although this observation was found to be statistically significant it was argued that the small change in latency with frequency would have no practical significance and could therefore be ignored. However, in light of the present results, this argument is revisited, and it turns out that an increased change of the delay with frequency by 0.5 ms (between 5700 and 1400 Hz) would move the Chirp 3 delay function in Fig. 2 to a function located between those corresponding to Chirp 4 and Chirp 5. Thus, it appears that the cochlear-neural delay model based on the derived-band latencies has progressively larger changes of the delay with frequency the lower the stimulus level. Such a model would explain the observed change in chirp efficiency from Chirp 3 toward Chirp 4 and Chirp 5 when the level is lowered from 40 to 20 dB nHL.

At 60 dB nHL, which is the maximum level used here, Fig. 4 demonstrates that the largest mean ABR amplitude is

FIG. 7. Grand average ABR waveforms obtained from all 10 normal-hearing subjects (20 ears). The computation of these waveforms is based on time-shifting the individual ABR recordings—see text for details.

generated by Chirp 2. The amplitude distribution is relatively skewed and dominated by Chirp 1 and Chirp 2 as shown in Fig. 6. Thus, the use of the mean parameter values (Chirp 3) does not lead to the most efficient chirp at 60 dB nHL, whereas values corresponding to a smaller change of the delay with frequency would be more adequate (corresponding to Chirp 1 and Chirp 2).

The cochlear-neural delay model is based on derived-band ABR latencies obtained at a click level of 60 dB nHL, and therefore, it is expected to constitute an optimal delay model for the design of a chirp to be used at this stimulus level. Contrary to this expectation, we observe a significant drop in the ABR amplitude for Chirp 3 (as well as for Chirp 4 and 5) when the level is increased from 40 to 60 dB nHL (Fig. 4 and Table I). Similar results were reported by Fobel and Dau (2004) for the M-chirp and O-chirp (see their Fig. 5), and were also found by Elberling and Don (2008), where Chirp 3 was shown to be more efficient at 50 than at 60 dB nHL. As described earlier by Elberling and Don (2008) we offer the following explanation for this finding. At low stimulus levels each frequency component of a chirp (or a click) excites a restricted location in the cochlea, but for higher levels the excitation broadens—especially due to upward spread of excitation (Eggermont and Don, 1980, and Folsom, 1984). The concept of the chirp implies that each frequency component has an individual timing in accordance with the specified delay model. Therefore, at higher levels, each cochlear location will be excited by a broader range of frequency components each having a *different* timing. At each location, this will cause a desynchronization, or temporal smoothing, of the resulting compound excitation, which causes the corresponding ABR to drop in amplitude. However, a shorter chirp will lower the desynchronization, and therefore, partly compensate for the negative effect of the

broader excitation. In the present study, the negative effect is especially apparent for Chirp 5, which at 60 dB nHL generates a highly disrupted ABR waveform—see the corresponding grand average ABR in Fig. 7 (top right).

As shown in Fig. 5, the observed mean latencies at 20 and 40 dB nHL move slightly and gradually to smaller values as the stimulus changes from the click toward higher chirp number (larger delays). This is probably due to the fact that the band of frequencies, which dominates the generation of the broad-band ABR at these low levels ($\sim 2\text{--}4$ kHz—see, e.g., Eggermont and Don, 1980; Folsom, 1984),⁸ is presented earlier and earlier in time the higher the chirp number. However, the above argument related to upward spread of excitation may explain the conspicuous shortening of the latency with increasing chirp number, which is observed at 60 dB nHL. If a lower frequency component excites a higher frequency location in the cochlea through upward spread of excitation, the resulting contribution to the ABR from that frequency location will appear with a shorter latency because the lower frequency component is presented earlier in time than the higher frequency component which normally is mapped to that location. The different mechanisms discussed here could be further evaluated within a framework of a mathematical model which describes the relationship between cochlear processing and patterns of the ABR (e.g., Dau, 2003).

When evaluating the results presented here, caution should be exercised when attempting to generalize the conclusions, like for instance by extending the conclusions to other stimulus levels or to other latency-frequency models than have been studied here. In this respect the present study has a specific limitation because variants of the same latency-frequency model, i.e., a power function model [Eq. (1)], has been used to generate the different chirps. However,

the results reported from the use of other types of models (Fobel and Dau, 2004; Elberling *et al.*, 2007) are not in opposition to the results and conclusions reported here. The delay model by Neely *et al.* (1988) based on frequency-specific ABR latencies (also mathematically described by a power function), gives the following relative latency-frequency functions:

- At 60 dB nHL (85 dB SPL), a function that is located between the functions for Chirp 1 and 2 (shown in Fig. 2).
- At 40 dB nHL, a function between Chirp 2 and 3.
- At 20 dB nHL, a function between and around Chirp 4 and 5.

The three latency-frequency functions by Neely *et al.* (1988) are shown, for comparison, by the broken lines in Fig. 2 (for other latency-frequency models see, e.g., Elberling *et al.*, 2007, Fig. 1). Therefore, the changes with level of the latency functions by Neely *et al.* (1988) are in line with those for the chirps producing the highest ABR amplitudes in the present study.

The present results imply that for the optimal recording of ABRs in normal-hearing subjects the chirp should be changed systematically with stimulus level, i.e., the higher the level the shorter the chirp. Whether such a stimulus/level scheme would work for the recording in hearing-impaired subjects is not known, because no significant experience presently exists for the use of chirp stimuli in individuals with hearing loss. Since the concept of the chirp presumes (1) a normal cochlear frequency-location mapping and (2) a normal frequency tuning, it is conceivable that the chirp characteristics, which are advantageous for the recording in normal-hearing subjects, may not show the same effects in subjects with different types and degrees of hearing impairment. For instance, in an ear with a flat sensorineural hearing loss and missing outer hair cells, the ABR can only be recorded at relatively high stimulus levels, and therefore we would predict that only a minor advantage would be observed of using a chirp rather than a click. In an ear with a ski-slope, sensorineural hearing loss, with preserved hearing up to about 2000 Hz, we would predict that, over a large range of stimulus levels, the chirp would be more efficient than the click because the negative effect on the chirp response from upward spread of excitation probably would be reduced.

Because the advantage of the chirp over the click depends on the frequency specificity and tuning properties of the cochlea, it would be interesting to evaluate whether the chirp could be used to study the relative role of inner and outer hair cells or similar physiological details.

V. SUMMARY AND CONCLUSION

ABR responses to click and chirp stimuli are studied in ten normal-hearing subjects (20 ears). Five different chirps designed by systematically changing the parameters of the cochlear-neural delay model by Elberling and Don (2008) have been used and evaluated at three presentation levels. In previous work it has been demonstrated repeatedly that chirps are more efficient than clicks for evaluating cochlear

function. Our aims and main hypotheses for the present study are based on the notion that stimulus level is one of the main determinants of the efficiency of the chirp. In particular, we hypothesize that (1) chirps with relatively larger durations are more efficient at low levels of stimulation because the change of the delay with frequency increases at the lower levels and (2) the loss of chirp efficiency at higher levels is due to spread of excitation. The ABR amplitude and latency results obtained are consistent with these hypotheses. Because the results have only been obtained in normal-hearing individuals, it is unclear whether similar results will be obtained in hearing-impaired individuals. Nonetheless, it is suggested that the use of chirps for evaluating cochlear function may need to consider the level of presentation. The advantage of the chirp appears to be dependent on cochlear frequency specificity and therefore, chirps may be used to study the physiological underpinnings—for instance, the role of inner and outer hair cells.

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¹Previously (Elberling *et al.*, 2007; Elberling and Don, 2008), we have used the term “cochlear delay.” However, because the modeled delay includes both cochlear and neural components, the term “cochlear-neural delay” will be used throughout this paper.

²The Neely *et al.* chirp used by Elberling *et al.* (2007) was level independent and used the frequency-latency model information valid for 90 dB SPL (Neely *et al.* 1988); this level corresponds approximately to 65 dB nHL.

³In 19 of the 39 normal-hearing control subjects in the experiment by Don *et al.* (2005) a repeated set of derived-band measures were acquired. From these recordings the repeatability of the latency-measure in the different derived bands can be calculated.

⁴The CE marking is a conformity mark that is mandatory for most products in the European Economy Area.

⁵A calibration check performed after termination of the experimental study revealed a general calibration error of 2.4 dB. The actual presentation levels were therefore 62.4, 42.4, and 22.4 dB nHL.

⁶For click ABRs the peak is wave V and for chirp ABRs the peak most often resembles wave V but one doesn't always feel confident in using this term in connection with chirp ABRs, because earlier peaks often cannot be identified or they appear at odd latencies.

⁷Because the relative standard deviations are large (about 15%–30% of the means) the use of standard errors instead of standard deviations provides visually a better overview of the data structure in Fig. 4.

⁸In the paper by Eggermont and Don (1980) each derived band was characterized by its lower cut-off frequency. In later studies—and particularly in Don *et al.* (1998) and Don *et al.* (2005), which have been used to generate the present cochlear-neural delay model (Elberling and Don, 2008)—the geometrical mean of the two cut-off frequencies have been used to characterize the derived bands. For the present evaluation, the results from Eggermont and Don (1980) are therefore shifted up in frequency by half an octave.

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