

New Clicklike Stimuli for Hearing Testing

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Abstract

The click stimulus generally used for newborn hearing screening generates a traveling wave along the basilar membrane, which excites each of the frequency bands in the cochlea, one after another. Due to the lack in synchronization of the excitations, the summated response amplitude is low. A repetitive click-like stimulus can be set up in the frequency domain by adding a high number of cosines, the frequency intervals of which comply with the desired stimulus repetition rate. Straight-forward compensation of the cochlear traveling wave delay is possible with a stimulus of this type. As a result, better synchronization of the neural excitation can be obtained so that higher response amplitudes can be expected. The additional introduction of a frequency offset enables the use of a q-sample test for response detection. The results of investigations carried out on a large group of normal-hearing test subjects have confirmed the enhanced efficiency of this stimulus design. The new stimuli lead to significantly higher response SNRs and thus higher detection rates and shorter detection times. Using band-limited stimuli designed in the same manner, a "frequency-specific" hearing screening seems to be possible.

Key Words: Phase-compensated stimuli, cochlear delay time, newborn hearing screening, frequency-specific hearing screening

Abbreviations: ABR = Auditory Brainstem Response; AABR = Automatic Auditory Brainstem Response; ASSR = Auditory Steady-State Response; C click = Cosine click; C-FO click = Cosine Frequency Offset click; CP click = Cosine Phase-compensated click; CP-FO click = Cosine Phase-compensated Frequency Offset click; DPOAE = Distortion Product Oto-Acoustic Emission; FFT = Fast Fourier Transform; FO = Frequency Offset; OAE = Oto-Acoustic Emission; PI = Performance Index; SNR = Signal-to-Noise Ratio; TEOAE = Transient Evoked Oto-Acoustic Emission

Sumario

El estímulo click, generalmente usado para el tamizaje auditivo de recién nacidos, genera una onda viajera a lo largo de la membrana basilar que estimula cada una de las bandas de frecuencia en la cóclea, una después de la otra. Debido a una falta de sincronización en la estimulación, la amplitud de la respuesta sumada es baja. Se puede establecer un estímulo repetitivo tipo clic en el dominio de frecuencia por medio de la adición de un alto número de cosenos, los intervalos de frecuencia que cumplen con la tasa deseada de repetición de estímulos. Es posible una compensación directa del retardo en la onda viajera coclear con un estímulo de este tipo. Como resultado, se puede obtener una mejor sincronización de la excitación neural, por lo que pueden esperarse amplitudes de respuesta mayores. La introducción adicional de una frecuencia que contrarreste permite el uso de una prueba de muestra "q" para detección de la respuesta. Los resultados de investigaciones realizadas en grandes grupos de sujetos con audición normal han confirmado la eficiencia aumentada de este diseño de estímulo. Los nuevos estímulos llevan a una SNR de respuesta significativamente más alto y por ende, a tasas mayores

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de detección y a tiempos menores de detección. Utilizando estímulos de banda limitada diseñados de la misma forma, un tamizaje auditivo frecuencia-específico parece posible.

Palabras clave: Estímulos de fase compensada, tiempo de retardo coclear, tamizaje auditivo de recién nacidos, tamizaje auditivo frecuencia-específico

Abreviaturas: ABR = Respuesta auditivas del Tallo Cerebral; AABR = Respuestas Auditivas Evocadas Automáticas; ASSR = Respuesta Auditivas de Estado Estable; C click = click de coseno; C-FO click = click del coseno compensado de la frecuencia; CP click = click de coseno de fase compensada; CP-FO = click de coseno de fase compensada de la frecuencia; DPOAE = Emisión Otoacústica por Producto de Distorsión; FTT = Transformación Rápida de Fourier; FO = compensación de la frecuencia; OAE = Emisión Otoacústica; PI = Índice de Desempeño; SNR = Tasa de Señal/Ruido; TEOAE = Emisión Otoacústica Evocadas por Transitorios

Over the past ten years, tremendous progress has been made in the early identification of hearing disorders in newborns with the help of universal newborn hearing screening. The two most commonly used screening procedures are based on the otoacoustic emission (OAE) and auditory brainstem response (ABR) (Thornton et al, 2003).

Recording transient-evoked otoacoustic emission (TEOAE) or distortion-product otoacoustic emission (DPOAE) is the favored technique in many projects that focus on neonatal hearing screening (Kok et al., 1993; Maxon et al., 1993; Schorn, 1993; White et al., 1994; Watkin, 1996; Levi et al., 1997; Lutman et al., 1997; Aidan et al, 1999; Gorga et al., 2000). OAE recording is quick and easy to carry out. There are, however, several disadvantages: OAEs may be affected by debris and fluid in the external and middle ear, resulting in referral rates of 5% or more during the first 24 hours after birth (American Academy of Pediatrics, 1999). A high referral rate increases the cost of the time-consuming and expensive diagnostic procedure for those neonates who fail the screening test. Furthermore, since the outer hair cells of the inner ear are the source of OAEs, OAE recording does not detect eighth nerve or auditory brainstem dysfunction. Auditory neuropathy or neural conduction disorders, therefore, will - in principle - not be detected by OAEs (Joint Committee on Infant Hearing, 2000). The auditory brainstem response reflects activity of the cochlea, auditory nerve and auditory brainstem. Consequently, the sensitivity of an ABR-based screening procedure is in principle higher, as compared to OAE-based proce-

dures, since eighth nerve and/or auditory brainstem dysfunctions will be detected. Moreover, ABR recording is less affected by middle or external ear debris (American Academy of Pediatrics, 1999), leading to a lower referral rate compared to OAE (higher specificity). One disadvantage of ABR is due to the fact that recording of ABRs is more time-consuming than the recording of OAEs. Stürzebecher et al., 2003, introduced a procedure that remedied this considerably. The auditory steady-state response, ASSR, evoked with a high stimulus repetition rate at around 90 clicks/s can be detected through an efficient statistical test procedure after just 20 to 50 seconds. The quick screening algorithm in conjunction with the handheld BERAphone® (MAICO Diagnostic), which does not require the adhesion of electrodes, led to a total examination time of short duration comparable with that of OAE-based procedures.

Click-ASSR evoked by stimulus rates in the order of 90 clicks/s, is normally believed to consist of activity from within the brainstem (e.g. Picton et al. 2003). When it is used for infant screening it can as well be referred to as ABR-screening and, if detected automatically, as AABR-screening. In the present paper we will therefore use these later terms.

To date, AABR screening equipment has generally used an excitation level of 40 dBnHL. Yet with infants suffering from a mild hearing loss, there is danger of a false pass (Johnson et al., 2005). In order to guarantee an adequately high specificity (low refer rate) at a stimulus level reduced to 35 dBnHL or even down to 30 dBnHL, the AABR screening algorithm needs to be optimized further. A major step in this

direction lies in optimizing the auditory stimulus.

The click used up to now is a broadband signal which generates a traveling wave that stimulates all frequency areas of the cochlea, one after the other. The velocity of the traveling wave is highest in the basal part of the cochlea and slows down towards the apex. Due to the resulting greater synchronization of excitation in the basal part of the cochlea, only the higher frequency ranges contribute effectively to the click-evoked activity. The traveling wave delay in the more apical part of the cochlea is responsible for considerably dispersed responses from this area. For this reason, the spatio-temporally summated response does not achieve the amplitude that would result from a more synchronous excitation. Lütkenhöner et al., 1990, and Dau et al., 2000, have, for this reason, proposed a rising chirp as a more effective stimulus. The rising chirp is a broadband stimulus that attempts to compensate for the traveling wave delay. Lütkenhöner et al., 1990, used the latency differences of frequency-specific ABRs as a measure of the cochlear delay. Dau et al., 2000, calculated the temporal dispersion on the basis of the cochlear model of de Boer, 1980, using the mapping-parameters of Greenwood, 1990. Both publications report greater ABR amplitude for the chirp stimulation, as compared to the standard click. The results, however, have not yet been confirmed in a large clinical study and therefore, the chirp has not been introduced in the clinical practice.

Recently, Stürzebecher et al. (2006) introduced new stimuli for the recording of frequency-specific ASSR. Within a specified frequency range, each of these stimuli consists of the sum of several cosines, the frequency intervals of which comply with the desired stimulus repetition rate. The phase of the cosines was corrected in accordance with the cochlear model of de Boer (1980) using the parameters of Greenwood (1990), so that despite different frequencies corresponding to multiples of the repetition rate, all cosines contribute to a maximum of deflection along the basilar membrane. These new stimuli proved to be clearly more efficient in generating frequency-specific ASSRs, especially around 500 Hz, as compared to a stimulus without any phase correction.

It would be quite easy also to construct a broadband stimulus by adding a large num-

ber of cosines corresponding to distributed frequencies in the frequency range between approx. 200 Hz and 8 kHz, the individual cosines of which were also phase-corrected. As with the two rising chirps described above, greater response amplitudes should be expected for this stimulus than with the standard click. A greater response amplitude will lead to a shorter test time and an increased specificity of the ABR based hearing screening.

Nevertheless, hearing screening with a broadband stimulus has the disadvantage that hearing losses with elevated thresholds at low and mid-frequencies and normal hearing at high frequencies can be missed (Picton et al., 2002). By using the frequency domain design described above, a band-limited stimulus covering the low and mid-frequency range and a band-limited stimulus covering the high frequency range can easily be created with a precisely selected cut off frequency between the two stimuli e.g. 1500 Hz. A hearing screening with the simultaneous application of these two "frequency-specific" stimuli would prevent a newborn with a hearing loss at low and mid-frequencies and normal hearing at high frequencies from producing a false pass. At the same time, the hearing screening would provide initial information on the characteristics of the hearing loss.

The aim of the present study is to test the efficiency of the new phase-compensated broadband stimuli on a large group of normal-hearing juvenile volunteers and to compare it with that of the standard click as well as the flat chirp according to Dau et al. (2000). It is further the aim of the study to investigate the feasibility of performing "frequency-specific" hearing screening in two frequency bands.

METHODS

Description of the New Stimuli for Hearing Screening

In contrast to the conventional generation of a click in the time domain, a click-like stimulus can be created in the frequency domain through the addition of a large number of cosines with a fixed frequency difference. Here, the frequency difference is selected in accordance with the desired stimulus repetition rate.

In a previous article (Stürzebecher et al., 2003), we found a click repetition rate of approx. 90/s to be optimal for newborn hearing screening. For this reason, a repetition frequency $f_r = 90$ Hz (exactly 89.89 Hz) corresponding to a repetition rate of 90/s is chosen for all stimuli in the present experiments.

The stimulus signal can then be described by Equation (1):

$$y_1(t) = \frac{1}{n} [\cos(2\pi f_1 t) + \cos(2\pi \{f_1 + 1f_r\}t) + \dots + \cos(2\pi \{f_1 + (n-1)f_r\}t)]$$

$$y_1(t) = \frac{1}{n} \sum_{k=0}^{n-1} \cos(2\pi \{f_1 + kf_r\}t) \quad \text{Eq. 1}$$

where
 n = number of cosines
 f_1 = lowest frequency of n cosines
 f_r = repetition frequency corresponding to the stimulus repetition rate
 The highest frequency f_h of the n cosines is then
 $f_h = f_1 + (n-1)f_r$

A ripple between the individual pulses of the stimulus can be effectively reduced by halving the amplitudes of the cosines with the lowest and the highest frequency, in accordance with Equation (2).

$$y_2(t) = \frac{1}{n-1} \sum_{k=0}^{n-1} a_k \cos(2\pi \{f_1 + kf_r\}t) \quad \text{Eq. 2}$$

where
 $a_k = 0.5$ for $k=0$ and $k=n-1$,
 $a_k = 1$ for all other k .

The stimulus in accordance with Equation (2) is shown in Figure 1a. The time functions of this stimulus and of the following are shown to the left and the corresponding amplitude spectra are shown to the right. The stimulus shown in Figure 1a will subsequently be described as cosine click (C click).

The construction of the stimuli from individual cosines provides a means to define both the frequency range and the amplitude spectrum of each stimulus. It also offers the possibility of introducing a frequency-dependent phase correction in order to compensate for the propagation time in the cochlea. The cochlea model from de Boer (1980) was first selected as a basis for this correction. The constants given by Greenwood (1990) have been used in de Boer's equation. Figure 2 shows the cochlea delay of this model relative to 100 Hz. A phase angle, Φ_k , which compensates for the cochlea delay time, has been introduced

into Equation (2):

$$y_3(t) = \frac{1}{n-1} \sum_{k=0}^{n-1} a_k \cos(2\pi \{f_1 + kf_r\}t + \varphi_k) \quad \text{Eq. 3}$$

where Φ_k = frequency-dependent phase displacement calculated from the cochlea delay time

The time function of the C click, which is phase-compensated in accordance with Equation (3), is shown in Figure 1b. The amplitude spectrum of the stimulus is identical to that presented in Figure 1a, but the phase spectrum will of course be different. The C click with phase correction will subsequently be labeled with the additional abbreviation P (CP click).

In the case of frequency-specific ASSR stimuli using a modulated pure tone carrier, it is standard practice to select the carrier frequency to be an integer multiple of the modulation frequency. This leads to the following problem already described by Stürzebecher et al. (2006): interference may arise between the lower frequencies of an electrical stimulus artifact and the higher harmonics of the response, particularly in the case of the 500 Hz stimulus. However, this also applies to the C click and CP click described above. In Figure 1b the position of the first six harmonics of the response is marked by arrows that indicate the frequencies at which interference can occur. If a frequency offset, f_{off} , is now introduced into Equation (3) as shown in Equation (4), this will cause a displacement of the stimulus frequency spectrum (frequency offset); by contrast, the first harmonic of the response will still be located at f_r and the higher response harmonics will still be at multiples of f_r .

$$y_4(t) = \frac{1}{n-1} \sum_{k=0}^{n-1} a_k \cos(2\pi \{f_1 + kf_r - f_{off}\}t + \varphi_k) \quad \text{Eq. 4}$$

where $0 < f_{off} < f_r$

However, the rigid coupling between the frequencies of the stimulus and the repetition frequency, f_r , is lost with any selection of f_{off} ; this results in a periodic cycling of the resulting stimulus. Specifically, if

$$f_{off} = \frac{f_r}{2}$$

is selected, a phase-coupling across 2 periods of f_r arises and the result is an alternating stimulus as shown in Figure 1c. The harmonics of the response continue to appear at

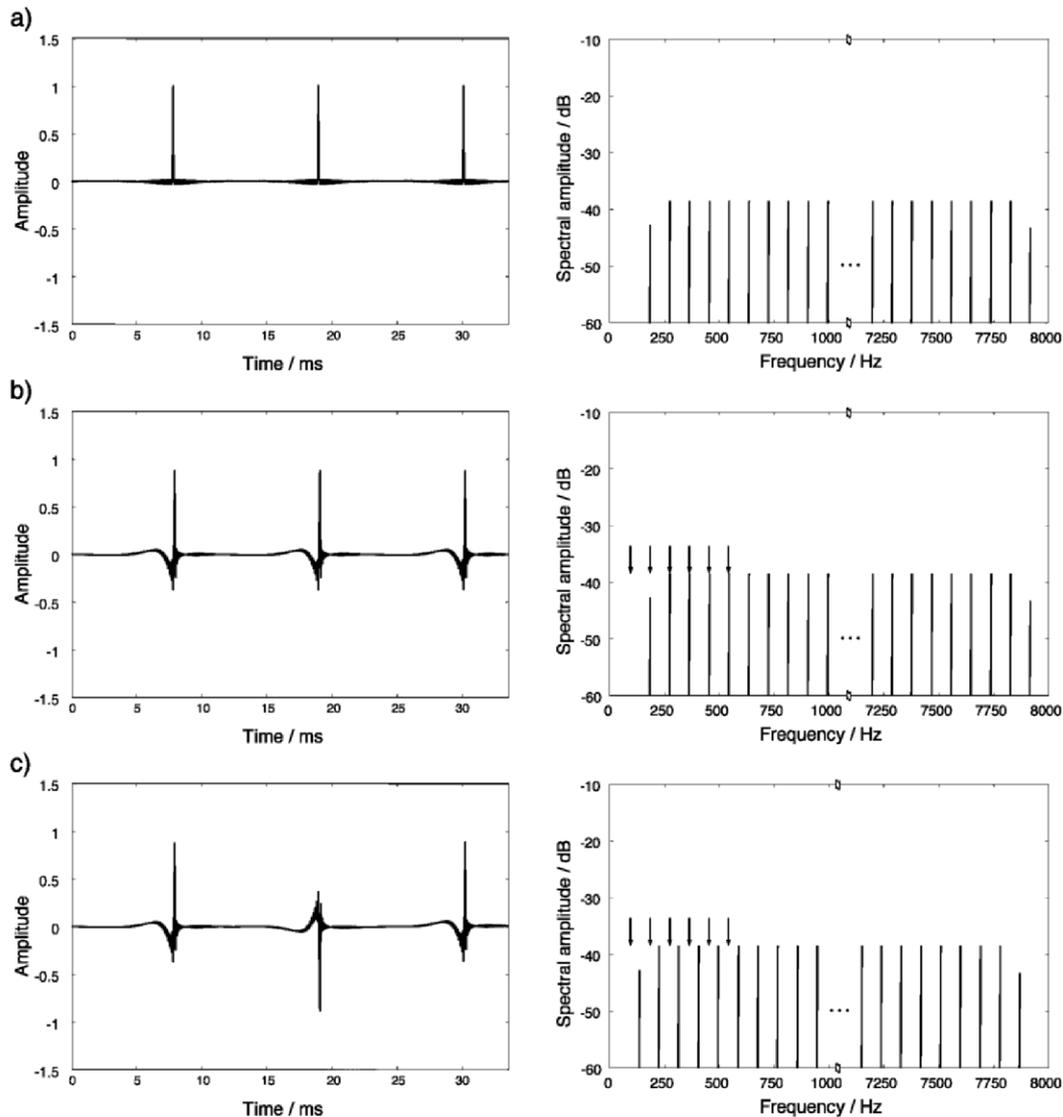


Figure 1. Presentation of the time functions and the frequency amplitude spectra of the new stimuli: *a*, 87 added cosines. The first and last cosines are only half the amplitude of the other cosines in order to reduce the ripple between the stimuli (C click); *b*, 87 added cosines in accordance with *a*, but with correction for the cochlea delay time (CP click); *c*, 87 added cosines in accordance with *b* with additional frequency offset (CP-FO click). The arrows indicate the position of the first six harmonics of the response.

the same frequencies as in Figure 1b; however, the frequency spectrum of the stimulus is displaced to the left by $f_r/2$.

The CP click stimuli with frequency offset will subsequently be denoted with the additional abbreviation FO (FO = frequency offset): CP-FO click.

Since the frequency offset leads to an alternating stimulus, then, conversely, it may be concluded that alternating a stimulus waveform will result in a frequency offset between the spectral components of the stimulus and those of the response.

For this reason, an alternating polarity was introduced for the standard click and the flat chirp, since it was not readily pos-

sible to introduce a frequency offset in the frequency domain. Figure 3 shows the time function of the flat chirp according to Dau et al. (2000) alternated by multiplying the amplitude values of each second chirp by -1.

The following stimuli were used in the study (exact frequency values have been rounded to integers):

i Broadband stimuli

1. C click 180 Hz - 7910 kHz (87 cosines)
2. CP click 180 Hz - 7910 kHz (87 cosines)
3. C-FO click 135 Hz - 7865 kHz (87 cosines)
4. CP-FO click 135 Hz - 7865 Hz (87 cosines)
5. Standard click, pulse width 125 μ s
6. Alternating standard click, pulse width 125 μ s

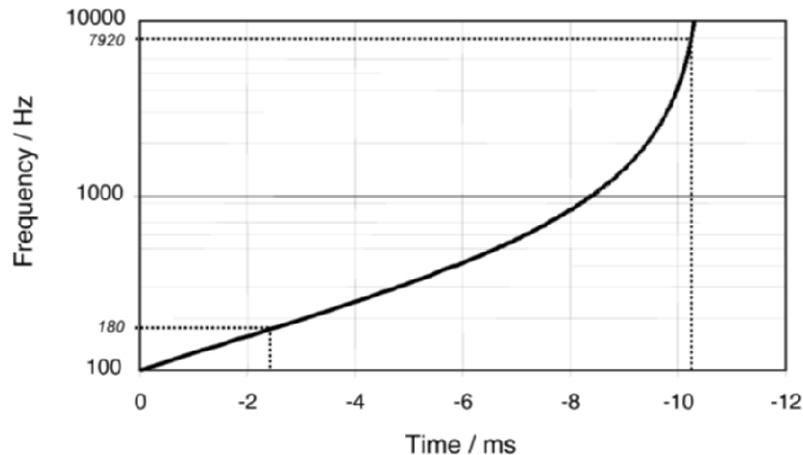


Figure 2. Cochlea delay in accordance with the model of de Boer (1980). The delay is plotted relative to 100 Hz.

7. Flat chirp (Dau et al., 2000)
8. Alternating flat chirp (Dau et al., 2000)

ii Band-limited stimuli

9. Low C click 180 Hz - 1438 kHz
(15 cosines)
10. Low CP click 180 Hz - 1438 kHz
(15 cosines)
11. Low CP-FO click 135 Hz - 1393 kHz
(15 cosines)
12. High C click 1528 kHz - 7910 kHz
(72 cosines)
13. High CP click 1528 kHz - 7910 kHz
(72 cosines)

It was not necessary to introduce a frequency offset for stimuli Nos. 12 and 13, since here the spectral components of the stimulus artifact and the first six response harmonics are not overlapping.

The stimuli were presented individually (not simultaneously) at a rate of 90/s and at a stimulus level of 40 dBnHL. Calibration of each stimulus was obtained in a subgroup of 10 participants from the group of young test subjects with normal hearing used for the investigations in the present study (see "Subjects" section below). The stimuli were presented in random order. For each stimulus, the individual, subjective hearing threshold was established using a bracketing method and a step size of 1 dB. The mean threshold for each stimulus was calculated from the individual threshold levels.

Subjects

The AABR testing for this study was carried out using two samples of test subjects (subject sample 1 and subject sample 2).

Subject sample 1 (70 normal-hearing

individuals, 14 males and 56 females aged 17–34 years) was also used for testing a series of other stimuli developed for frequency-specific AABR; see Stürzebecher et al. (2006), where subject sample 1 is described in more detail.

The number of possible test conditions was restricted because only two recording sessions, each lasting about one hour, could be planned with each test subject. Some test subjects did not show up at the second meeting. The failure of the test subjects to reappear affected all stimuli equally because the stimuli were tested in a random order. For this reason, the number of pairs available for paired comparisons (see "Analyses" section below) is smaller than the number of test subjects specified above, and may differ slightly across the different stimulus conditions.

Because the test time was limited to two test sessions, only the stimuli Nos. 1, 2, 5, 7, 9, 10, 12, 13 were tested with subject sample 1 (in addition to the stimuli of the previous study). As explained above, it was not possible to examine all stimuli with subject sample 1. Therefore, the frequency offset stimuli and the alternating stimuli (Nos. 3, 4, 6, 8, 11) were tested with subject sample 2.

Subject sample 2 consisted of 22 normal-hearing individuals, 4 males and 18 females aged 19–32 years. The behavioral thresholds for pure tones at the frequencies 500, 1000, 2000, and 4000 Hz were 10 dB HL or lower. As in subject sample 1, most of the participants were students at the school of speech therapy and most were, therefore, females.

The subjects reclined comfortably on an

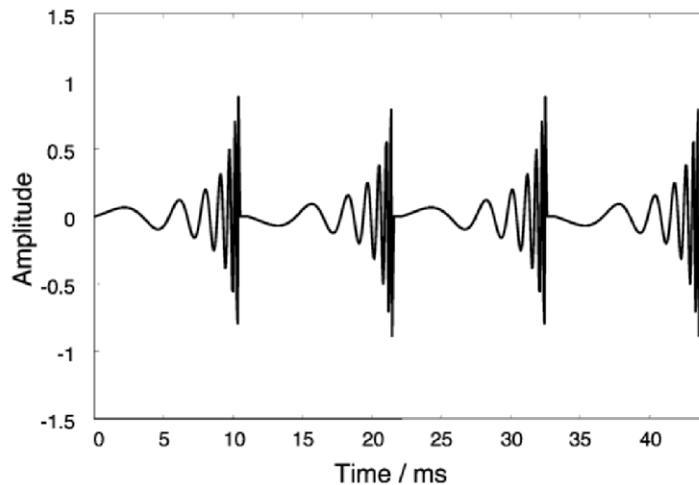


Figure 3. Time function of the alternating flat chirp (Dau et al. 2000). The flat chirp was alternated by multiplying the amplitude values of each second chirp by -1.

examination couch in a soundproof chamber. They were asked to relax and, if possible, to sleep during the recording session. However, quite a few were not able to sleep.

Recording

The recording conditions were the same as described in detail in Stürzebecher et al., 2006. The recording electrodes were placed at the vertex (C_z) and at the ipsilateral mastoid, whereas the ground electrode was placed on the forehead. For the recording, the MB11-2 equipment (MAICO Diagnostics GmbH) was used without the BERAPHone® but with headphones (HDA 280, Sennheiser) and a separate preamplifier. The EEG was continuously stored on hard disc during the recording for the subsequent off-line analysis.

During the recording, the modified Rayleigh test (PC*, Moore, 1980) was applied to the first harmonic of the response with a sequential test strategy (Stürzebecher et al. 2005). The following test regime was used: the general duration of the data collection was at least 155 seconds, even if a response had already been detected before this time had elapsed. If no response was detected during the 155 seconds, recording was continued until detection, and was then terminated approx. 10 seconds later. The data recording was terminated after 300 seconds if no response had been detected.

Analyses

Analyses were carried out off-line, as described in detail by Stürzebecher et al.,

2006. The EEG segments were divided into epochs with duration of about 1 second (1.024 s). Each epoch was transformed into the frequency domain by Fast Fourier Transformation (FFT). The frequency resolution was about 1 Hz ($0.976 \text{ Hz} = 1/1.024 \text{ s}$).

In the frequency domain, the efficiency of the stimuli was assessed by means of the detection rate, the detection time and the SNR of the first harmonics. In addition to these parameters, the overall performance of the different stimuli was characterized by a performance index (PI), which is calculated by $PI = \text{detection rate}/\text{detection time}$.

The first 150 epochs (record length 153.6 seconds) were used for calculation of the SNR of the first response harmonics in the frequency domain. The SNR of the harmonics was calculated in the following way:

$$SNR = \frac{S^*}{\bar{N}} \quad \text{Eq. 5}$$

with

S^* - amplitude (response + noise) of the first response component (first harmonics) in the frequency spectrum

\bar{N} - mean background noise amplitude estimated from 60 noise components in the frequency spectrum. Thirty noise components were taken from the left and right sides of the corresponding response component.

For the detection of the responses to the stimuli without frequency off-set or without alternation (stimuli Nos. 1, 2, 5, 7, 9, 10), a one-sample test that only makes use of the first harmonic of the response spectrum

should be applied. For the higher harmonics, there was the problem, already described, of the harmonics overlapping a possible stimulus artifact. Here, the response is detected using the modified Rayleigh test (Moore, 1980) including a further modification (Cebulla et al., 2006). This additional modification uses the spectral amplitudes weighted by the mean spectral noise (\bar{N}), instead of the ranked amplitudes as proposed by Moore (1980). With the standard click and the flat chirp, there is the problem that the first harmonic of the response and the stimulus artifact may overlap. Nevertheless, the modified Rayleigh test was used to detect the response in these two stimulus conditions, although it cannot be ruled out that some influence could have been exerted by a stimulus artifact.

For the other stimuli with frequency offset or alternation, the response was detected using the q-sample uniform scores test (Mardia, 1972) including a modification (Cebulla et al., 2006). While Mardia's q-sample uniform scores test only uses the ranked phases, the original phase values were used in the modified version of this test. In addition, the spectral amplitudes weighted by the mean spectral noise were also used in the modified version of the test. While the modified Rayleigh test only tests one harmonic (usually the first harmonic), the first six response harmonics were included in the modified q-sample test.

The tests were carried out with an error probability of $\alpha = 0.1\%$. During the off-line analysis, a sequential test strategy to detect the response was applied as follows: first, the test was applied to the first 10

epochs. Next, the sample was increased by 1 epoch and tested again. This was repeated until a response was detected or the maximum available sample size had been reached.

The critical test values for repeated testing were determined by applying the procedure described by Stürzebecher et al. (2005). Here it was possible to guarantee the predetermined error probability of $\alpha = 0.1\%$.

To test the differences between the results (detection rate, detection time and SNR), the statistical tests used paired comparisons on dependent samples. However, as explained above, the number of possible pairs is smaller than the number of test subjects because it was not possible to obtain recordings from all stimuli in all participants.

The differences between the various detection rates were tested for significance using the McNemar Test (Siegel, 1956). The detection time was calculated from the minimum number of epochs necessary to detect the response. The detection time was set to the maximum investigation time (300 s) when a response could not be detected. The differences in detection time for the different AABR stimuli were tested using the Wilcoxon matched pairs signed rank test (Siegel, 1956). The SNR differences were also tested using the Wilcoxon matched pairs signed rank test. The SNR of the recordings was also included, even when no response had been detected.

RESULTS

The results for the broadband stimuli without frequency offset or without

Table 1. Detection rate [%], median detection time [s], performance index, PI [%/s] and SNR (mean and (SD)) of the first harmonic of the responses to four different broadband stimuli tested with subject sample 1: Standard click (No. 5), C click (No. 1), CP click (No. 2), and Flat chirp (No. 7). Response detection is made by a one-sample test. The difference in results for stimuli Nos. 1, 2, and 7 compared to stimulus No. 5 was tested for significance and the respective p-values are shown in the table (n.s. = not significant). N is the number of comparison pairs.

Stim. No.	Stimulus	Detection Rate [%]	Median Detection Time [s]	Performance Index	SNR (SD)
5 N=62	Standard click	94.3	27	3.49	10.4(6.4)
1 N=62	C click	95.7 n.s.	28 n.s.	3.42	10.5(5.9) n.s.
2 N=62	CP click	98.6 n.s.	20 p<<0.01	4.93	14.2(8.2) p<<0.01
7 N=62	Flat chirp	98.6 n.s.	18 p<<0.01	5.48	15.9(8.1) p<<0.01

alternation are detailed in Table 1. The results were obtained with subject sample 1. Only a one-sample test could be used to detect the responses to these stimuli (see above). With the phase-corrected click (CP click (2)), the results obtained were clearly more favorable compared to those with the standard click (5): the detection rate is significantly higher and the detection time significantly shorter. The performance index PI is correspondingly greater. The higher degree of efficiency of the CP click (2) compared to the standard click (5) is also reflected in the significantly larger SNR of the first harmonic. The results with the flat chirp (7) as compared to the standard click (5) can be described in the same manner. The results for the C click (1), which was constructed from the summation of cosines without phase-correction, do not differ significantly from those of the standard click (5).

The difference between the SNR for the CP click (2) and the flat chirp (7) is not significant ($p > 0.2$), the detection rate for both stimuli is identical (98.6%) and the minimal difference in detection time is also not

significant ($p > 0.5$).

To illustrate the gain obtained by compensating for the cochlea delay with the CP click in contrast to the C click (and to the standard click as well), Fig. 4 shows the grand averages of the responses recorded in subject sample 1 to both stimuli in the time domain (on the left) and in the frequency domain (on the right). In the time domain, the response amplitude to the CP click is about 1.35 times larger than that to the C click. This corresponds to the ratio of the corresponding mean SNRs of the first harmonics of the two responses in the frequency domain given in Table 1 (about 1.35).

The results shown in Table 2 were obtained with the smaller subject sample 2. On the grounds of the frequency offset or the alternation of stimuli, the testing could be carried out with a q-sample test that incorporates not only the fundamental (1. harmonic) but also the harmonics 2 to 6 of the response. As a result, although all SNRs in Table 2 are somewhat lower compared to the corresponding values in Table 1, detection rates of 100% and shorter detection time are obtained for all stimuli.

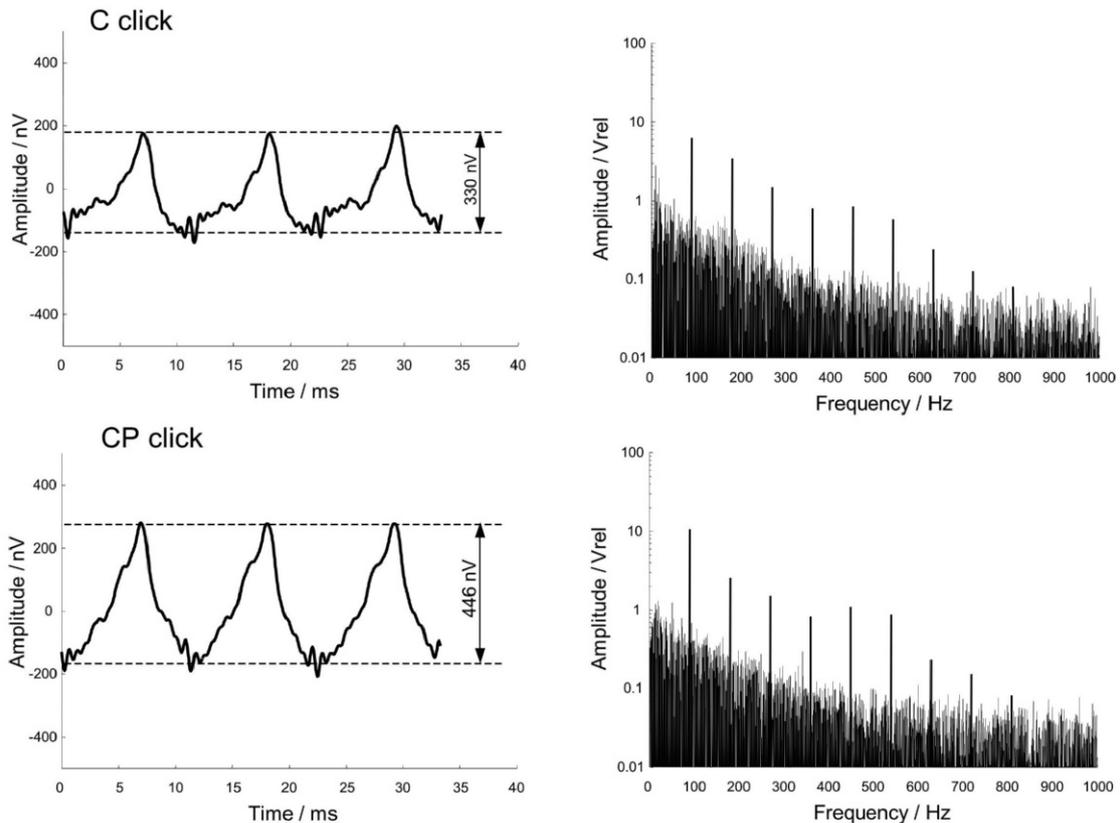


Figure 4. Grand averages of the response to the C click (1) and the CP click (2) in the time domain (*left*) and the frequency domain (*right*). As expected, both curves show a small electrical stimulus artifact overlaying the response.

Table 2. Detection rate [%], median detection time [s], performance index, PI [%/s] and SNR (mean and(SD)) of the first harmonic of the responses to four different alternating broadband stimuli tested with subject sample 2: Alternating standard click (No. 6), C-FO click (No. 3), CP-FO click (No. 4), and Alternating flat chirp (No. 8). A q-sample test that incorporates the first six harmonics is used for the response detection. The difference in results for stimuli Nos. 3, 4, and 8 compared to stimulus No. 6 was tested for significance and the respective p-values are shown in the table (n.s. = not significant). The difference in SNR between stimuli 4 and 8 is significant (p<0.01). N is the number of comparison pairs.

Stim. No.	Stimulus	Detection Rate [%]	Median Detection Time [s]	Performance Index	SNR (SD)
6 N=22	Alternating standard click	100	21	4.76	7.3(3.9)
3 N=22	C-FO click	100	20 n.s.	5.00	7.8(4.4) n.s.
4 N=22	CP-FO click	100	16 p<0.02	6.25	11.5(5.3) p<0.01
8 N=22	Alternating flat chirp	100	15 p<0.02	6.67	14.6(7.5) p<<0.01

This naturally gives the higher PI values in Table 2. For the stimuli with frequency offset or with alternation in Table 2, the ranking of stimulus efficiency is the same as for the corresponding stimuli in Table 1. The alternating standard click (6) and the C-FO click (3) (without phase compensation) rank with almost the same PI below the CP-FO click (4) (with phase compensation) and the alternating flat chirp (8). For the last two stimuli (Nos. 4 and 8), the detection times are significantly shorter and the SNRs significantly greater than for the alternating standard click (6). In comparing the efficiency of the CP-FO click (4) and the alternating flat chirp (8), Table 2 gives somewhat clearer indication of the tendency, already suggested in Table 1, of a difference in SNR between the flat chirp (7) and the

CP click (2). The SNR of the first harmonic achieved with the flat chirp is significantly greater (p<0.01) than that obtained with the CP click. Nevertheless, it is noticeable that the difference in detection time is non significant (p>0.05), and therefore a minimal difference between the PIs is observed. While the SNR reflects the condition of the first harmonic, the detection rate and detection time were obtained from the q-sample test that includes the first six harmonics. Therefore, Figure 5 shows the mean SNR from each of the first six harmonics of the responses to both stimuli. Only for the first harmonic a significant difference exists between the two stimuli in favor of the flat chirp. For the harmonics 2, 3, 5 and 6, the differences are not significant. For harmonic 4, the SNR is signifi-

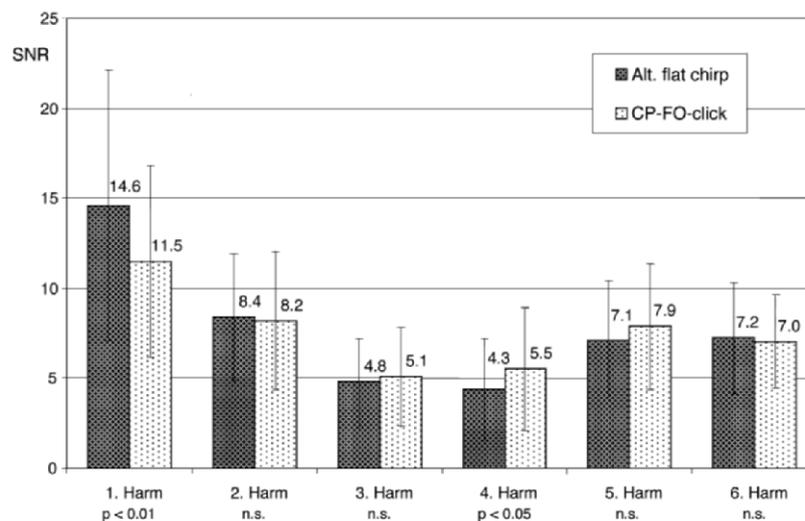


Figure 5. Mean SNRs for the first six harmonics of the responses to the alternating flat chirp and the CP-FO-click. The error bars represent the standard deviation of the individual SNR's.

cantly greater for the CP-FO click than for the flat chirp.

Table 3 lists the results for the band-limited stimuli. The compensation for the cochlea delay applied to the Low CP click (10) leads to a significantly greater SNR, compared to the corresponding stimulus without compensation (Low C click (9)). Testing with a one-sample test a significantly shorter detection time is obtained for the Low CP click compared to the Low C click. The increase in detection rate is not significant. The PI for the Low CP click (10) is about 1.5 times greater compared to that for the Low C click (9).

Table 3 also shows the results for the alternating Low CP click (Low CP-FO click (11)). The tests with this stimulus, in contrast to the other stimuli in Table 3, were carried out with subject sample 2. A q-sample test could be used here for response detection. A detection rate of 100% was given with a much shortened detection time. A high PI naturally follows.

As was to be expected, the phase compensation had only a minimal effect with the High CP click (13), compared to the High C click (12). The detection rate for both stimuli is 100%. The minimal differences in SNR and detection time are not significant.

DISCUSSION

In considering the pros and cons of the OAE- and ABR-based screening methods, a two-step screening procedure, beginning

with an OAE test and followed by an ABR test for all infants who failed the OAE test, was proposed by the NIH Consensus Statement (1993). The advantage of combining these two different tests is that the high referral rate of the first test with an OAE screening device will be lowered by the subsequent ABR-based test. However, this procedure only enhances specificity. The sensitivity of the OAE-based test procedures cannot be improved by a subsequent ABR test, because, contrary to the opinion of Dolphin (2004), with the two-step screening procedure only some of the babies suffering from retrocochlear hearing disorders (for example, auditory neuropathy [AN]) will probably be detected. Infants with AN or other retrocochlear abnormalities but normal OAE will already have passed the OAE test and therefore will not be considered for ABR testing.

A more optimal solution is more likely achieved with a purely AABR-based hearing screening procedure.

It was the aim of the present study to test new stimuli which could enhance the efficiency of an AABR screening procedure.

As expected, the differences in results in Table 1 for the C click constructed of cosines and the standard click are not significant, since the C click constructed in the frequency domain is for all practical purposes equivalent to the standard click presented at the same stimulus rate. In contrast, the compensation for the cochlea delay with the CP click leads to significant-

Table 3. Detection rate [%], median detection time [s], performance index, PI [%/s] and SNR (mean and(SD)) of the first harmonic for the responses to five different band-limited stimuli: Low C click (No. 9), Low CP click (No. 10), Low CP-FO click (11), High C click (No. 12), and High CP click (No. 13). For the detection of the responses to the stimuli Nos. 9, 10, 12, and 13 a one-sample test was used. For the detection of the response to stimulus No. 11, a q-sample test was used. The differences in the results for stimuli Nos. 10 and 9 and the differences in the results for stimuli Nos. 13 and 12 were tested for significance and the respective p-values are shown in the table (n.s. = not significant). The stimuli No. 9, 10, 12 and 13 were tested with subject sample 1, stimulus No. 11 with subject sample 2. N is the number of comparison pairs.

Stim. No.	Stimulus	Detection Rate [%]	Median Detection Time [s]	Performance Index	SNR (SD)
9 N=64	Low C-click	95.7	34	2.81	7.8(4.6)
10 N=64	Low CP click	98.6 9/10 n.s.	24 9/10 p<0.05	4.11	9.8(5.6) 9/10 p<0.01
11 N=22	Low CP-FO click	100	15	6.67	12.8(5.6)
12 N=70	High C click	100	20	5.00	12.4(6.2)
13 N=70	High CP click	100	21 12/13 n.s.	4.76	13.9(7.1) 12/13 n.s.

ly higher detection rate, shorter detection time, and higher SNR compared to the values obtained with the standard click. The compensation for the cochlea delay appears to produce better synchronization of the excitation of the neural units along the cochlear partition and as a result, larger amplitudes of the spatio-temporal summated response. The flat chirp (Dau et al., 2000) is also designed to compensate for the cochlea delay. With the results given in Table 1, there is, except for the detection rate, a tendency that the flat chirp is more efficient than the CP click. However, with the non-alternated flat chirp, it is not possible to rule out some influence from a possible stimulus artifact.

Comparing the results listed in Table 2 with those for the corresponding stimuli in Table 1, it is noticed that all the SNRs in Table 2 are somewhat lower. Here, two differences of method come into question:

- i) The results in Table 1 were obtained from subject sample 1 (70 test subjects); those of Table 2 from subject sample 2 (22 test subjects).
- ii) The results featured in Table 2 have been achieved, in contrast to those of Table 1, with alternating stimuli (standard click, flat chirp) or with stimuli with frequency offset (C-FO click, CP-FO click) and detected with a q-sample test.

It is difficult to assess which of the two methodological differences exerted the greater influence. However, an alternated stimulus can be expected to be less efficient than a non-alternated stimulus, since the summation of neural responses to stimuli of differing polarity leads to lower compound amplitudes. The values for detection rate and detection time in Table 2 show however, that the somewhat lesser efficiency of the alternated stimuli is made up for by the ability to use a q-sample test for the response detection, incorporating not only the first harmonic but also the higher harmonics. Therefore, despite the lower SNR, the detection rate is higher and the detection time lower than for the corresponding stimuli in Table 1, for which only a one-sample test could be used. Consequently, the PI is greater for all stimuli of Table 2 than for the corresponding non-alternated stimuli in Table 1.

In Table 2 the efficiency of the stimuli reflects the same ranking as in Table 1. In other words, even with the alternated stim-

uli of Table 2, compensation for the cochlea delay with the CP-FO click, as compared to the C-FO click, leads to better values for detection rate, detection time (performance index), and SNR. However, the results in Table 2 also demonstrate a slight but significant advantage of the alternated flat chirp over the CP-FO click.

Considering the results from these two stimuli, it is noticeable that despite the significantly larger SNRs achieved with the alternated flat chirp, as compared to the CP-FO click, the PI for the flat chirp is only minimally greater. Figure 5 shows one of the reasons for this finding. The SNRs given in Tables 1 and 2 are the mean values for the first harmonic. Figure 5 shows the mean SNR values of the first six harmonics for the alternated flat chirp and the CP-FO click. Here it is clear that the gain in SNR with the flat chirp is restricted to the first harmonic. With the higher harmonics, there are no significant differences in favor of the flat chirp. With harmonic 4, the SNR of the response to the CP-FO click is even significantly larger. The cause of this difference may be related to a difference in waveform between the responses elicited by the two stimuli.

Comparing Figure 1c and Figure 3 it is evident that the temporal waveforms of CP-FO click and the alternated flat chirp are very different. In view of this difference one would expect to observe a difference in performance. To understand this effect, the design and construction of the two stimuli have to be considered:

The CP-FO click was constructed in the frequency domain by adding a large number of cosines with uniform amplitude. The frequency difference of the cosines was selected in accordance with the desired stimulus repetition rate. The cochlea delay calculated from the cochlea model from de Boer (1980) was used for the phase compensation of the individual cosines whereby the model delay was considered to be the phase delay. In contrast, the flat chirp according to Dau et al. (2000) was constructed in the time domain also using the cochlea delay derived from the de Boer model. However, Dau et al. (2000) regarded the model delay to be the group delay.

(The terms "phase delay" and "group delay" may be explained as follows: The phase delay indicates how much a steady-state cosine of a specific frequency is delayed from the input to the output of a

system (here: a linear model of the cochlea) whereas the group delay indicates how much the envelope of a signal formed by a narrow group of frequencies is delayed from the input to the output).

In another study (Elberling et al. 2007) we analyze in more detail different models of the cochlear traveling wave delay and its relation to cochlear excitation in response to repetitive clicks. This leads to the construction of three different chirps and a standard click which are compared in an AABR experiment using 49 normal-hearing individuals. The results from this study indicate that the models of the traveling wave delay can be used to describe the group delay of a linear model of the cochlea. Further, it demonstrates differences in ASSRs recorded in response to chirps constructed from different delay functions.

When a specific model of the cochlear traveling wave delay has been identified to produce an efficient chirp in adults it may also be valid for small children, because functionally, the cochlea is already mature at this age - at least for mid and lower frequencies (Eggermont and Ponton, 1991; Abdala and Sininger, 1996). Therefore, it can be expected that the results bring about an increased efficiency (shorter test time, increased specificity) of the AABR based newborn hearing screening.

The results listed in Table 3 can help answer the question as to whether a "frequency-specific" newborn hearing screening is possible. Stimulation at low levels with band-limited stimuli only causes excitation of a restricted area of the basilar membrane. The number of single units that contributes to the spatio-temporal summated response is, therefore, less than the number of contributing units in response to a broadband stimulus. When band-limited stimuli are used for newborn screening, the detection rate still has to be high (high specificity) and the response detection not too long (short detection time). The results for the Low-band clicks in Table 3 demonstrate the advantage of correcting for the cochlea delay (stimulus 10 and 11 compared to stimulus 9), as well as the advantage of alternating the stimulus (FO) that enables the use of a q-sample test for the response detection (stimulus 11 compared to stimuli 9 and 10). Since the velocity of the traveling wave and hence the synchronization of the

neuronal units is considerably greater in the basal part of the cochlea than in the apical part, phase compensation of the High CP click (13) has only minimal effect, as compared to the High C click (12).

First and foremost, the stimuli 11 (low and mid-frequency stimulus) and 13 (High-frequency stimulus) can be considered suitable for "frequency-specific" hearing screening. Given the high detection rates and short detection times achieved with a significance level of $\alpha=0.1\%$, a "frequency-specific" hearing screening with these band-limited stimuli seems feasible.

In the present study all stimuli were applied sequentially i.e. one at the time. For a "frequency-specific" hearing screening, the two band-limited stimuli could admittedly be tested one after the other, given the short median detection times, but a simultaneous application of the stimuli would be desirable. With simultaneous stimulation, however, interaction or masking between the two stimuli may be anticipated (John et al., 2002). Therefore, a future study should be carried out in order to evaluate the extent to which simultaneous stimulation reduces the efficiency of each of the two stimuli. Further, such a study should investigate whether stimulus interference may be reduced, for instance by means of inserting a frequency gap between the two stimuli and reducing the stimulus level to 35 dBnHL.

In the present study, new stimuli were described, which, because of the compensation for the cochlea delay, achieve a better synchronization of the excitation on the basilar membrane and consequently evoke significantly greater responses than a standard click. A previous study of ours (Cebulla et al., 2006) showed that the application of a q-sample test in the frequency domain, incorporating several harmonics in the response detection, is of greater advantage than the use of a one-sample test that only incorporates the first harmonic. The results of the present study confirm this finding again. The application of a combination of the new stimuli and the use of a q-sample test for response detection leads to significantly greater efficiency in AABR testing in young adults and most likely also in newborns. A "frequency-specific" AABR hearing screening which tests the low-to-mid and the high frequency ranges separately but simultaneously, can possibly be developed.

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