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New Efficient Stimuli for Evoking Frequency-Specific Auditory Steady-State Responses

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Abstract

ASSR is a promising tool for the objective frequency-specific assessment of hearing thresholds in children. The stimulus generally used for ASSR recording (single amplitude-modulated carrier) only activates a small area on the basilar membrane. Therefore, the response amplitude is low. A stimulus with a broader frequency spectrum can be composed by adding several cosines whose frequency intervals comply with the desired stimulus repetition rate. Compensation of the travelling wave delay on the basilar membrane is possible with a stimulus of this type. Through this, a better synchronization of the neural response can be obtained and, as a result, higher response amplitudes can be expected, particularly for low-frequency stimuli. The additional introduction of a frequency offset enables the use of a q-sample test for the response detection, especially important at 500 Hz. The results of investigations carried out on a large group of normally hearing test subjects have confirmed the efficiency of this stimulus design. The new stimuli lead to significantly improved ASSRs with higher SNRs and thus higher detection rates and shorter detection times.

Key Words: ASSR, auditory steady-state response, cochlear delay time, hearing threshold assessment, objective audiometry

Sumario

Las respuestas auditivas de estado estable (ASSR) son una herramienta promisoria para la evaluación objetiva y con especificidad de frecuencia de los umbrales auditivos en niños. El estímulo generalmente utilizado para el registro de las ASSR (un portador único de amplitud modulada) sólo activa una pequeña área de la membrana basilar. Por lo tanto, la amplitud de la respuesta es baja. Un estímulo con un espectro de frecuencia más amplio puede crearse adicionando varios cosenos cuyos intervalos de frecuencia cumplen con la tasa deseada de repetición del estímulo.

Es posible la compensación del retardo en la onda viajera sobre la membrana basilar con un estímulo de este tipo. De esta forma, se puede obtener una mejor sincronización de la respuesta neural y, como resultado, se pueden esperar amplitudes de respuesta mayores, particularmente para estímulos de baja frecuencia. La introducción adicional de una frecuencia de compensación permite el uso de prueba de muestra "q" para la detección de la respuesta, especialmente importante a 500 Hz. Los resultados de la investigación conducidas en un grupo grande de sujetos con pruebas auditivas normales han confirmado la eficiencia de este diseño de estímulo. Los nuevos estímulos llevaron a una mejoría significativa de las ASSR con SNR más altos, y por tanto, a tasas mayores de detección y a tiempos menores de detección.

Palabras Clave: ASSR, respuesta auditiva de estado estable, tiempo de retardo coclear, evaluación del umbral auditivo, audiometría objetiva

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The auditory steady-state response (ASSR) has proven to be a promising tool for the objective frequency-specific hearing assessment in small children (Perez-Abalo et al, 2001; Dimitrijevic et al, 2002; Rance and Rickards, 2002; Firszt et al, 2004; Luts et al, 2004; Swanepoel et al, 2004). Traditionally, an amplitude-modulated tone is used as a stimulus. Such a stimulus has a frequency spectrum with three components: the carrier and two side band components separated from the carrier by the modulation frequency. With a modulation frequency between 70 and 100 Hz, the activated area on the basilar membrane is very narrow, and consequently the responses are highly frequency specific. The resulting ASSR is not sinusoidal, and in the frequency domain it is represented by several harmonics. The frequency of the first harmonic (fundamental wave) corresponds to the modulation frequency, and the higher harmonics are integer multiples of the modulation frequency (Cebulla et al, 2006). This fixed relationship between the modulation frequency and the position of the harmonics in the frequency spectrum provides a basis for an objective response detection using relatively simple statistical methods.

For objective response detection, one can either use a statistical test that uses only the first harmonic (one-sample test), which in the literature is the most commonly used detection method (Valdes et al, 1997; John and Picton, 2000; Perez-Abalo et al, 2001; Dimitrijevic et al, 2002; Rance and Rickards, 2002; Firszt et al, 2004; Luts et al, 2004; Swanepoel et al, 2004), or a suitable statistical test that uses both the first harmonic and several higher harmonics (q-sample test; Cebulla et al, 2006). Cebulla et al (2006) demonstrated that the detection performance can be increased by the inclusion of several harmonics. This is advantageous because the signal-to-noise ratio (SNR) of the response is very small (Cohen et al, 1991). Due to the low response amplitude, response detection close to the hearing threshold is difficult. Higher response amplitudes can be expected if the excited range on the basilar membrane is widened. For this reason, we previously designed a series of stimuli, consisting of several amplitude-modulated carriers (multicarrier stimuli [MC stimuli]; Stürzebecher et al, 2001), where the modulation frequency was identical for all carriers. The frequency difference between the carriers was one or two times the modulation frequency. With these stimuli, it was possible to increase the SNR of the response by a factor of up to 1.6. This increase is significant when one considers that an SNR increase by a factor of 1.4 only can be achieved by doubling the number of sweeps to be averaged (doubling the investigation time). Amplitude modulation with an exponential envelope as suggested by John et al (2002) or a mixed amplitude and frequency modulation (Cohen et al, 1991) also leads to a broadening of the excitation area on the basilar membrane. A certain compromise must be accepted between, on the one side, frequency specificity and, on the other side, response detectability. Our experiments with the multicarrier (MC) stimuli have shown an improvement of the ASSR detectability (Cebulla et al, 2006). However, a further increase in response SNR would be desirable, particularly at 500 Hz. The majority of authors who measured ASSR at the standard frequencies 500, 1000, 2000, and 4000 Hz found larger differences between behavioral and ASSR threshold (e.g., Rance et al, 1995; Perez-Abalo, 2001; Dimitrijevic et al, 2002; Herdman and Stapells, 2003; Luts and Wouters, 2004) or a smaller response amplitude and a corresponding lower incidence of significant responses (John et al, 2004) at 500 Hz compared to 1000 and 2000 Hz. Contrary to the above reports, the results from Rance et al, 2005, show larger differences between behavioral and ASSR threshold not only for 500 but also for 1000 Hz in comparison to 2000 Hz. The results from some authors demonstrate the same but less pronounced difficulties for 4000 Hz compared to 1000 and 2000 Hz (John et al 2004; Luts and Wouters, 2004). The more difficult conditions at 500 and 4000 Hz demonstrated by the results of the above cited authors correspond with our experience from some preliminary studies (not published). At these frequencies, response detection close to the behavioral hearing threshold seems to be more difficult than at 1000 and 2000 Hz.

The general problem at 500 Hz is that although a greater number of neural units are activated by the MC stimulus, the excitation is not sufficiently synchronous because of the low travelling wave velocity in the apical region of the cochlea. For this reason, the spatiotemporally summed response does not achieve the amplitude that would result with a more synchronous excitation.

The chirp is a known wide-band stimulus that can be used to evoke ABR. This stimulus is especially designed to compensate for the travelling wave delay. The compensation of the differences in travel time along the cochlear partition can either be based on the latency differences of frequency-specific ABR (Neely et al, 1988; Lütkenhöner et al, 1990) or on the temporal dispersion calculated using the cochlea model of de Boer (1980) (Dau et al, 2000). The ABR amplitude reported during chirp stimulation is significantly greater than with the usual click.

One of the aims of the present study was to design frequency-specific ASSR stimuli that stimulate the same broad area on the basilar membrane as the MC stimuli but that result in a more synchronous neural excitation. Such stimuli are expected to evoke responses with greater SNRs compared to those evoked by the MC stimuli.

Apart from this, there was another goal, namely, to improve on the conditions for detecting the ASSR, particularly at 500 Hz. One of the advantages of ASSR is that in the frequency domain the electrical stimulus artefact is located within the range of the carrier frequency and the sideband frequencies caused by the modulation. The response, however, is located at the harmonic frequencies of the modulation frequency. For this reason, an electrical stimulus artefact will normally not interfere as long as the statistical response detection is restricted to the first harmonic. However, we could demonstrate (Cebulla et al, 2006) that higher detection rates and shorter mean detection times are achieved if, in addition to the first harmonic, up to five higher harmonics are included.

Unfortunately, this technique can not be used at 500 Hz for the following reason: For the usual single-carrier stimulus with, for example, a carrier frequency of 540 Hz and a modulation frequency of 90 Hz, the lower sideband component coincides with the fifth harmonic of the response. Thus, an electrical stimulus artefact could lead to a false response detection when five harmonics are used. The circumstances are considerably more critical if the MC stimulus is applied at 500 Hz. Here, even the third harmonic of the response can be influenced by an electrical stimulus artefact. This means that particularly at 500 Hz, where optimal conditions for generating and detecting the response are necessary, a problem arises by the fact that a statistical test with the greater test power cannot be used to detect the response. For this reason, the second aim of the present study was to design ASSR stimuli which, in addition to compensating for the cochlea propagating time as described above, also produced a frequency offset between the frequencies of the stimulus and the harmonic frequencies of the response. Inclusion of the higher harmonics in the response detection would then not cause any problem.

The stimuli designed in accordance with the above guidelines are presented in the present study. The efficiency of these new ASSR stimuli is tested on a large group of young adults with normal hearing.

METHODS

Description of the New ASSR Stimuli

Traditionally, ASSR stimuli are generated by amplitude modulating a carrier (usually 500, 1000, 2000, and 4000 Hz) with a sinusoidal modulation signal (usually with a frequency in the range from 70 to 100 Hz). The envelope of such single-carrier stimuli shows relatively slow amplitude changes. The MC stimuli that were described above are constructed from several amplitude-modulated single-carrier stimuli and are characterized by faster amplitude changes (Stürzebecher et al, 2001). This corresponds to the broader range that is activated on the basilar membrane by the MC stimuli.

A stimulus that is suitable for evoking ASSR can also be created without modulation, by adding several sine or cosine waves, with a frequency difference corresponding to the desired repetition rate of the stimulus. The number of added sine or cosine waves determines the width of the area that is activated on the basilar membrane. In the following, the explanation is based on cosines, and the stimulus signal can then be described by Equation 1:

(1)

$$y_1(t) = \frac{1}{n}\left[\cos 2\pi f_l t + \cos(2\pi\{f_l + 1f_r\}t) + \ldots + \cos(2\pi\{f_l + (n-1)f_r\}t)\right]$$

$$y_1(t) = \frac{1}{n}\sum_{k=0}^{n-1}\cos(2\pi\{f_l + kf_r\}t)$$

n = number of cosines
f_l = 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
$f_h = f_l + (n - 1)f_r$.

In Figure 1 the time functions are shown to the left and the corresponding frequency amplitude spectra are shown to the right for n = 7. In these examples, the lowest frequency is f_l = 270 Hz and the repetition rate is f_r = 90 Hz. (The exact frequency values have been rounded to integers.) As a result, the stimulus has a bandwidth of approximately 270–810 Hz, and the center frequency is 540 Hz. A clear ripple is visible between the individual pulses of the stimulus in Fig. 1a. This ripple can be effectively reduced by halving the amplitudes of the cosines with the lowest and the highest frequency, in accordance with Equation 2.

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

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

The time function smoothed in accordance with Equation (2) is shown in Figure 1b. This stimulus will subsequently be described as a cosine stimulus (CW stimulus).

The construction of the CW stimuli from individual cosines provides a means to define both the frequency range and the frequency amplitude characteristic of the stimulus. It also offers the possibility to introduce 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 the basis for this correction. The constants given by Greenwood (1990) have been used in the equation of de Boer.

Figure 2 shows the frequency dependency of the cochlea delay relative to 100 Hz. The figure shows that the lowest frequency component (270 Hz) of the stimulus represented in Figure 1a and 1b is delayed by more than 3 msec compared to the highest one (810 Hz). A phase angle, φ_k, which compensates for the cochlea delay time, has been introduced into Equation 2:

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

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

The time function for n = 7 is shown to the left, and the frequency spectrum of this signal is shown to the right in Figure 1c. The amplitude spectrum of the stimulus is identical to that presented in Figure 1b, but the phase spectrum will of course be changed. In contrast to Figure 1b, the time function in Figure 1c shows a left-right asymmetry as a consequence of the introduced compensation of the cochlea delay time. The CW stimuli with phase correction will subsequently be labelled with the additional abbreviation "PC" (phase correction).

In general, it is standard practice to select the carrier and modulation frequencies in such a way that the carrier frequency is an integer multiple of the modulation frequency. This leads to the problem explained above for the MC stimuli: interference can exist between the lower frequencies of an electrical stimulus artefact with the higher harmonics of the response, particularly in the case of the 500 Hz stimulus. This also applies to the new CW stimuli described here. In Figure 1c, the position of the first six harmonics of the response is marked by arrows that indicate the frequencies at which interference can happen. 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); in 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.

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

where $0 < f_{off} < f_r$

However, the rigid coupling between the frequencies of the stimulus and the repetition

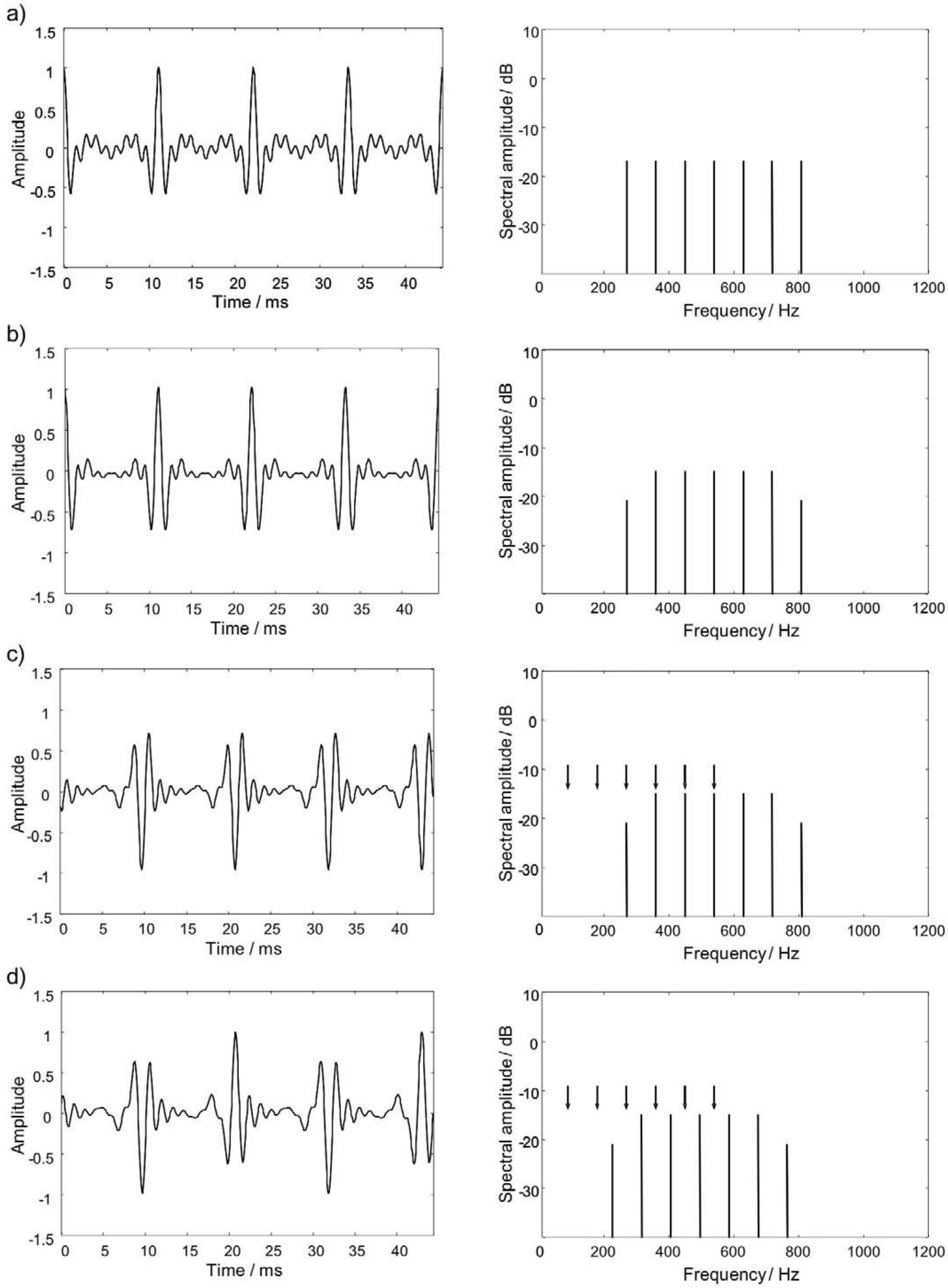

Figure 1. Presentation of the time function and the frequency amplitude spectrum of the new 500 Hz stimuli: *(a)* seven added cosines; *(b)* the first and seventh cosines with only half the amplitude of the other five cosines (7CW500); *(c)* seven added cosines in accordance with *b*, but with correction for the cochlea delay time (7CW500PC); *(d)* seven added cosines in accordance with *c* above with additional frequency offset (7CW500PC/FO). The arrows in *c* and *d* indicate the position of the first six harmonics of the response.

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 two periods of f_r arises, and the result is an alternating stimulus as shown in Figure 1d. The harmonics of the response continue to appear at the same frequencies as in Figure 1c; however, the frequency components of the stimulus are displaced to the left by $f_r/2$ in the spectrum.

The separation of the stimulus artefact from the harmonics of the response that is particularly important at 500 Hz is achieved through the described procedure. The CW stimuli with frequency offset will subsequently be denoted with the additional abbreviation "FO" (frequency offset).

In contrast to ASSR stimuli, which are made by modulation with a modulation signal having a complex nature, the ASSR stimuli used in the present study are precisely defined in the frequency domain. The frequency specificity of these stimuli is therefore well described.

The 1000, 2000, and 4000 Hz frequencies have also been included, although this study concentrates specifically on the problems at 500 Hz. Only a smaller advantage can be expected by correcting for the cochlea delay at these frequencies. However, it is necessary to check whether the stimuli constructed by the new method also are effective at these frequencies. In the present evaluation, the number of cosines for all stimuli is seven. However, at 4000 Hz, an additional stimulus consisting of 11 cosines was also constructed. The bandwidth of this stimulus corresponds to about one-third octave. It is only necessary at 500 Hz to implement the frequency offset to enable the use of a q-sample test (the use of six harmonics), and therefore, it was only applied for the 500 Hz stimulus.

As explained in section 2.2 ("Subjects"), the number of possible tests per subject is limited. For this reason, the usual ASSR stimulus (amplitude-modulated carrier) was only introduced for comparison at 500 Hz and 2000 Hz.

The following stimuli were used in the present study:

500 Hz Stimuli

1. AM500
   Usual amplitude-modulated 500 Hz carrier
2. 7CW500
   CW stimulus constructed with seven cosine frequencies
3. 7CW500PC
   As in 2 above, additionally with phase correction
4. 7CW500PC/FO
   As in 3 above, additionally with frequency offset

For the other stimuli, the descriptions follow those for the 500 Hz stimuli.

1000 Hz stimuli

5. 7CW1000
6. 7CW1000PC

2000 Hz stimuli

7. AM2000
8. 7CW2000
9. 7CW2000PC

4000 Hz stimuli

10. 7CW4000
11. 7CW4000PC
12. 11CW4000PC

The stimuli were presented with a rate of

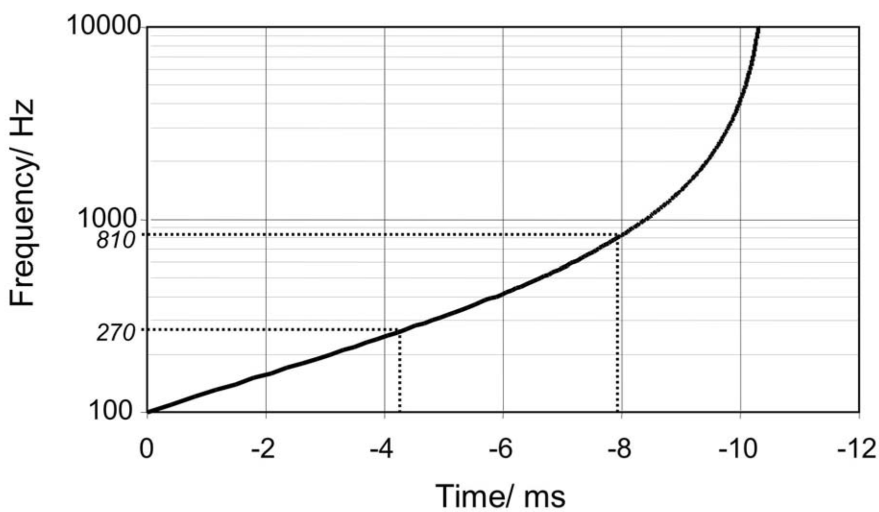

Figure 2. Cochlea delay shown in accordance with de Boer (1980). The time delay is plotted relative to 100 Hz.

90/sec and at a stimulus level of 30 dBnHL. Calibration of each stimulus was ascertained in a subgroup of ten participants from the group of young participants with normal hearing used for the investigations in the present study (see 2.2, "Subjects"). 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. The order of presentation of the stimuli was randomized.

Subjects

The test subjects in the study were 14 male and 56 female normally hearing individuals (aged 17–34 years). The behavioral thresholds for pure tones at the frequencies used in the experiments were 10 dB HL or lower. Most of the participants were students at the school of speech therapy, and most of the participants were therefore females. It is known that the ABR amplitude is somewhat larger in women than in men, and the ASSR probably behaves in a similar way. However, the results of the study were not influenced by the predominance of female participants as the investigation compared the ASSR amplitudes obtained at the different stimulus conditions and did not evaluate the absolute amplitudes.

The subjects reclined comfortably on an 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.

A series of other stimuli developed for hearing screening of newborns (to be published) were also tested using the same test subjects. The number of possible test conditions was limited because only two recording sessions, each of about an hour, could be planned with each test subject. Some test subjects did not appear at the second meeting. The failure of the test subjects to reappear affected equally both types of stimuli because they were tested in a random manner. For this reason, the number of pairs available for the different pair comparisons (see 2.5, "Analyses") is smaller than the number of test subjects specified above and may differ slightly across the different frequencies.

Recording

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 and a separate preamplifier.

The filter band pass was from 25 Hz (6 dB/octave) to 1.5 kHz (24 dB/octave). The analog-to-digital (AD) and the digital-to-analog (DA) conversion rates were 16 kHz. The EEG was stored continuously on hard disk during the recording. Independently of the subsequent off-line analysis, the data were transformed to the frequency domain by means of Fourier transformation during the data collection.

The modified Rayleigh Test (PC*; Moore, 1980) was applied to the first harmonic of the response with a sequential test strategy. To reduce the recording time, the following test regime was used: The general duration of the data collection was at least 155 seconds, even if a response already had been detected before this time had elapsed. If no response had been detected, the recording was continued until detection was obtained and was then terminated approximately ten seconds later. The data recording was terminated if no response could be detected after 300 seconds.

Analyses

Analyses were carried out off-line. Due to the different criteria for termination of the data collection, the length of the recorded EEG segments were not identical. The EEG segments were divided into epochs with a length of about one second (1.024 sec). Each epoch was transformed into the frequency domain using the fast Fourier transformation (FFT). The frequency resolution was about 1 Hz (0.976 Hz = 1/1.024 sec).

In the frequency domain, the efficiency of the stimuli was assessed by means of the SNR of the harmonics (first four or first six harmonics), by the detection rate, and the detection time. The overall performance of the different stimuli was characterized by a performance index (PI), which is calculated by PI = detection rate/detection time.

The first 150 epochs (record length 153.6 seconds) were averaged in the time domain for the SNR calculation. The average waveform was then transformed into the frequency domain by means of an FFT, providing a frequency resolution of about 1 Hz. The SNR of the harmonics was calculated in the following way:

$$SNR = \frac{S^*}{\overline{N}} \quad (5)$$

with

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

$\overline{N}$ = mean background noise amplitude estimated from 30 noise components in the frequency spectrum. The noise components were taken from the left and right sides of the corresponding response component.

For the 500 Hz stimuli without frequency off-set, the response detection was made with 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 (estimated from 30 spectral noise components each from the left and the right side of the response component) instead of the ranked amplitudes. For all other stimuli, the response detection was made with 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. Additionally, the spectral amplitudes weighted by the mean spectral noise were also used in the modified version. While the modified Rayleigh Test only tests one harmonic (usually the first harmonic), six response harmonics were included using the modified q-sample test. The tests were carried out with an error probability of $\alpha = 1\%$.

During the off-line analysis, a sequential test strategy was applied for the response detection in the following way: First, the test was applied to the first ten epochs. Next, the sample was increased by one 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 the repeated testing were determined with the procedure described by Stürzebecher et al (2005). Hereby the predetermined error probability of $\alpha = 1\%$ could be guaranteed.

To test the differences between the results (SNR, detection rate, detection time), the statistical tests had to be used on dependent samples; that is, pair comparisons were always carried out, because all subjects were subjected to all stimuli. However, as explained above, the number of possible pairs is smaller than the number of test subjects because it turned out that it was not possible to obtain recordings from all stimuli in all participants.

The statistical significance of the SNR differences with the different ASSR stimuli was tested using the Wilcoxon matched pairs signed rank test. The SNR of the recordings was also included even when no response had been detected. 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 sec) when a response could not be detected. Another possibility could have been to exclude all pairs in which one of the two stimuli had not evoked a detectable response. However, the chosen procedure provides more relevant information about the investigation time. The differences in detection time for the different ASSR stimuli were also tested using the Wilcoxon matched pairs signed rank test. The differences between the various detection rates were tested for significance using the McNemar Test (both tests: Siegel, 1956).

RESULTS

The test results for the 500 Hz stimuli are listed in Table 1. The table gives the detection rate, the median detection time, and the performance index, as well as the mean and standard deviation of the SNR of the first harmonic. It was the main aim of the study to develop new, more efficient stimuli, particularly at 500 Hz, that were superior to the usual amplitude-modulated single-carrier stimulus (AM500 in the first line of Table 1). The results with the new stimuli are presented on the second to fourth lines of Table 1. The differences between the three

Table 1. Detection Rate, Median Detection Time, Performance Index (PI), and Mean SNR (SD) of the First Harmonic for the Responses to the Traditional 500 Hz Amplitude-Modulated Stimulus (AM500) and Three New Stimuli

N	Stimulus	Statistical Test	Detection Rate (%)	Detection Time (Median) (s)	PI (%/s)	SNR (SD) First Harmonic
62	AM500	One-sample Test	74.2	109	0.68	4.03 (1.6)
62	7CW500	One-sample Test	77.4 ns	76 ns	1.02	5.08 (2.1) p = 0.036
62	7CW500PC	One-sample Test	85.5 p = 0.047	61 p = 0.013	1.40	5.41 (2.9) p = 0.005
56	7CW500PC/FO	q-sampleTest	91.1 p = 0.013	59 p < 0.001	1.54	5.13 (2.8) p = 0.048

Note: The difference of the results for the three new stimuli compared to the AM500 was tested for significance. The respective probabilities (p-values, ns = not significant) are also given. *N* is the number of comparison pairs.

new stimuli and the AM500 stimulus have been tested for significance. The resulting p-values are shown below the respective central parameter values for the new stimuli. Although the 7CW500 stimulus evokes a response with an SNR that is significantly greater than that of the AM500 (5.08 compared to 4.03, i.e., an increase by 26%), the detection rate (77.4% compared to 74.2%) and the detection time (76 sec compared to 109 sec) do not differ significantly.

In contrast, the introduction of the phase correction (7CW500PC) leads to a significant improvement for all three parameters compared to those obtained by the AM500 stimulus. The detection rate increases from 74.2% to 85.5%; the detection time decreases from 109 sec to 61 sec, and the SNR increases from 4.03 to 5.41.

If a frequency off-set in accordance with Equation 4 is introduced with the 7CW500PC/FO stimulus, it is possible to use a q-sample test to detect the response because the frequencies of a possible electrical stimulus artefact no longer coincide with the response harmonics. The recruitment of more response information leads to a further increase in detection rate to 91.1% and a further (slight) reduction in the detection time to 59 sec. The SNR of the first harmonic of the responses evoked with this stimulus is still significantly larger than that obtained with the AM500 stimulus but lower than that obtained with the 7CW500PC stimulus.

Table 2. Detection Rate, Median Detection Time, Performance Index (PI), and Mean SNR (SD) of the First Harmonic for Responses to Two New 1000 Hz Stimuli, Two New 2000 Hz Stimuli, Three New 4000 Hz Stimuli and for the Traditional 2000 Hz Stimulus (AM2000)

N	Stimulus	Statistical Test	Detection Rate [%]	Detection Time (Median) [s]	PI [%/s]	SNR (SD) First Harmonic
	7CW1000	q-sample Test	95.2	30	3.17	5.81 (2.8)
63	7CW1000PC	One-sample Test	88.9	37	2.40	
	7CW1000PC	q-sample Test	96.8	29	3.34	5.87 (3.3)
	AM2000	q-sample Test	82.0	103	0.80	3.68 (1.3)
	7CW2000	q-sample Test	91.8 ns	51 p = 0.003	1.8	5.23 (2.7) p = 0.003
57	7CW2000PC	One-sample Test	90.2	51	1.77	
	7CW2000PC	q-sample Test	95.1 p = 0.011	49 p < 0.001	1.94	5.69 (2.8) p < 0.001
60	7CW4000	q-sample Test	93.4	79	1.18	4.17 (1.3)
	7CW4000PC	q-sample Test	95.1	67	1.42	4.23 (1.8)
	11CW4000PC	One-sample Test	85.2	90	0.95	
	11CW4000PC	q-sample Test	96.7 ns	46 p = 0.017	2.10	4.32 (1.7) p = 0.038

Note: The difference in the results for the three new 2000 Hz stimuli has been tested compared to AM2000 for significance; 11CW4000PC was also tested compared to 7CW4000. The respective probabilities (p-values, ns = not significant) are also given. *N* is the number of comparison pairs. For the stimuli with phase correction (PC), the results obtained with the one-sample test are given in order to demonstrate the advantage of the q-sample test.

The performance index, PI, reflects the improvements gained by the new stimuli very well.

The results for 1000 Hz, 2000 Hz, and 4000 Hz obtained by application of the q-sample test are summarized in Table 2. For comparison to the q-sample test results, the one-sample results are also given for the stimuli with phase correction (PC). The reference condition, that is, the use of a stimulus that consists of an amplitude-modulated carrier, was only tested at 2000 Hz (AM2000).

As expected, the results for 7CW1000 and 7CW1000PC (q-sample test) do not differ significantly. The difference in the detection rate for the traditional AM2000 stimulus and the 7CW2000 stimulus (82.0% compared to 91.8%) is not significant. In contrast, the 7CW2000 detection time (103 sec compared to 51 sec) is significantly lower, and the SNR (3.68 compared to 5.23) is significantly larger than the AM2000 results. The cochlea delay time correction (7CW2000PC) leads to a further, but nonsignificant, improvement compared to the 7CW2000 results. Compared to the AM2000 stimulus, the detection rate (82% compared to 95.1%) is significantly higher, the median detection time (103 sec compared to 49 sec) is significantly lower, and the SNR (3.68 compared to 5.69) is significantly larger.

At 4000 Hz the following results are obtained. Compared to the 7CW4000 condition, the cochlea delay time correction (7CW4000PC) gives no improvement, and no significant increase in the detection rate is present, even when the wider 11CW4000PC stimulus is applied. However, compared to the 7CW4000 results, the detection time (79 sec compared to 46 sec) is significantly shorter, and the SNR (4.17 compared to 4.32) is significantly higher.

The performance index PI calculated from the detection rate and the median detection time is always highest for the stimuli with phase correction (PC) and the response detection by the q-sample test.

The mean SNRs for each of the response harmonics 1 to 4 to the 7CW500PC stimulus and those obtained in the AM500 condition are presented in Figure 3a. The corresponding SNR data for the response harmonics 1 to 6 at 2000 Hz are shown in Figure 3b.

The restriction at 500 Hz to only present four harmonics was necessary because the fifth to seventh response harmonics coincide with a possible electrical stimulus artefact from the AM500 stimulus. In contrast, the higher harmonics of the 2000 Hz response lie sufficiently far from any electrical stimulus artefact. The figures confirm our earlier results (Cebulla et al, 2006) that higher harmonics with significant amplitudes are present even in ASSRs evoked by the traditional amplitude-modulated stimuli (the AM500 and AM2000). For the new stimuli, the information carried by the higher harmonics appears to be even more pronounced compared to the amplitude-modulation stimulus condition. A one-sample test that only uses the first harmonic quite obviously neglects a significant part of the available response information for the detection.

Figure 4 shows the combined frequency distribution of the detection time for the four stimuli: 7CW500PC/FO, 7CW1000PC, 7CW2000PC, and 11CW4000PC. Presentations of each of the four frequencies were not reasonable because the sample size was too small for the individual frequency distributions. A frequency bin-width of 10 sec was chosen for this presentation. The frequency distribution of the detection time provides the following results at the selected stimulus level of 30 dBnHL: The maximum of the distribution corresponds to a detection time in the range of 20 to 30 sec; responses were detected within 50 sec in about 54% of the recordings; responses were detected within 100 sec in about 77% of the recordings; and finally, responses were detected within 300 sec in about 95% of the recordings. Thus, in 5% of the recordings, a response could not be detected within the maximum recording time (300 sec).

DISCUSSION

In objective frequency-specific assessment of hearing threshold using auditory-evoked potentials, there are in general greater differences at 500 Hz between the objective (electrophysiological) and the subjective threshold. This applies to simple tone burst ABR, to notched-noise ABR, and to the threshold assessed by means of ASSR. This is mainly due to the poor synchronization between the excitation of individual nerve fibers and is a consequence of the lower speed

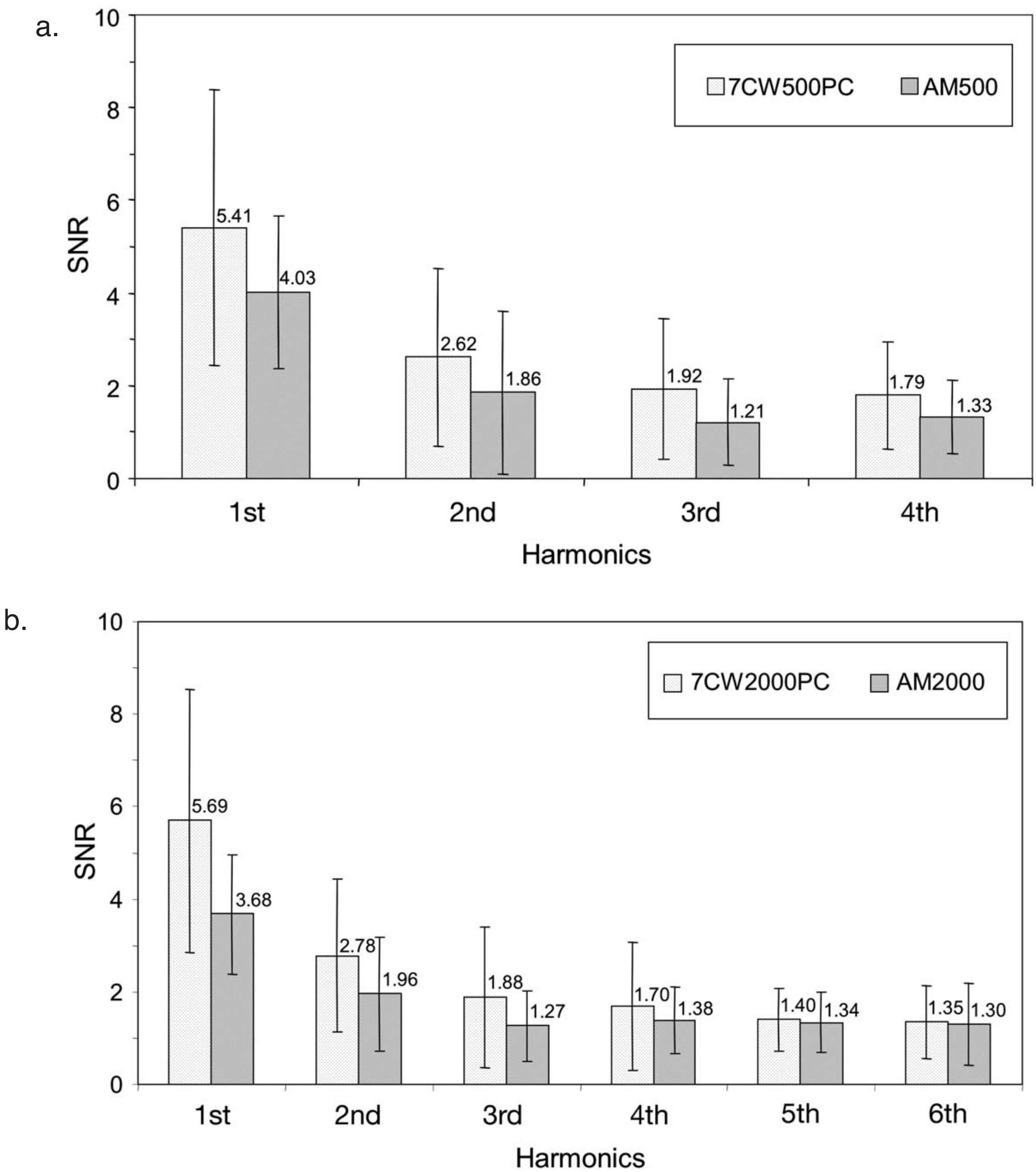

Figure 3. Mean SNR *(a)* for the first four harmonics of the responses to the 500 Hz stimuli, AM500 and 7CW500PC, and *(b)* for the first six harmonics of the responses to the 2000 Hz stimuli, AM2000 and 7CW2000PC.

of the travelling wave in this low-frequency region of the cochlea compared to the basal region. In the case of ASSR, there is the additional factor that the traditional stimulus (amplitude-modulated carrier) only activates a narrow frequency range. This applies to all frequencies, not just to 500 Hz. Although the resulting stimulus is highly frequency specific, the response is correspondingly very small and therefore difficult to detect. If the frequency spectrum of the stimulus is widened, a larger response is to be expected, at least at higher frequencies. The reduction of the resulting frequency specificity can be accepted. However, at 500 Hz the introduced spectral widening does not lead to any significant improvement, probably because of the poor synchronization in this frequency range. A higher synchronization of the excitation can be achieved through compensation of the cochlea delay corresponding to the individual frequency components in the broadened 500 Hz stimulus. The results demonstrate that such measure

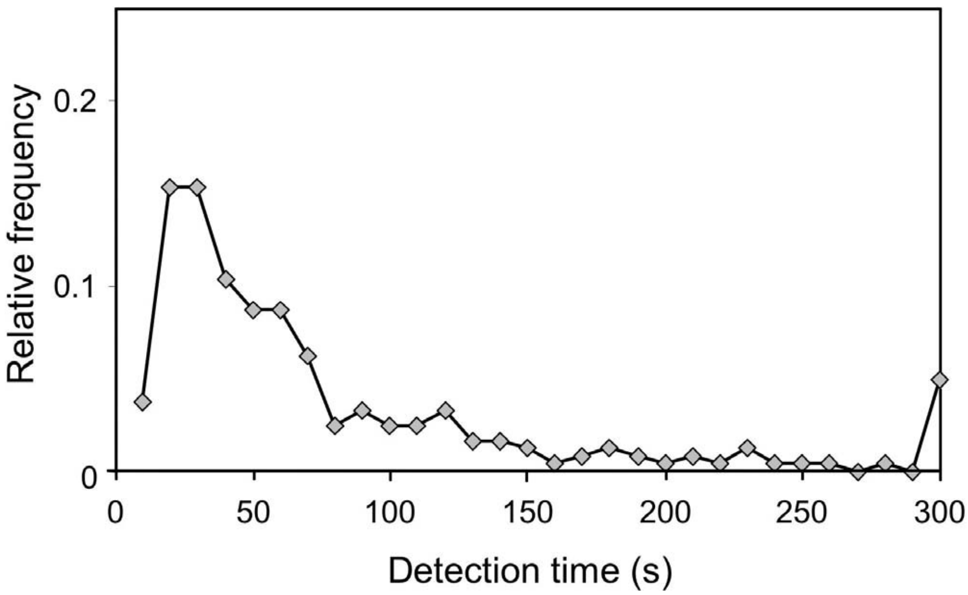

Figure 4. Frequency distribution of the detection times across the four stimuli: 7CW500PC/FO, 7CW1000PC, 7CW2000PC, and 11CW4000PC. The bin-width is 10 sec.

indeed provides a higher response amplitude.

In the experiment reported here, de Boer's cochlea model has been used to describe the characteristics of the human cochlea. However, as indicated by Fobel and Dau (2004), other models may be even better suited as a basis to compensate for the cochlear delay. When the optimal model has been identified, it may also be valid for small children, as the cochlea is functionally already mature at least for mid and lower frequencies at this age (Eggermont and Ponton, 1991; Abdala and Sininger, 1996).

It was the aim of the study presented here to test the new stimulus design on a group of adult participants with normal hearing and with particular attention to ASSR recordings at 500 Hz. It was expected that the introduction at 500 Hz of three novelties in the stimulus design would increase the detectability at this low frequency. The results have confirmed this expectation. Although the frequency widening from three spectral lines (AM500) to seven spectral lines (7CW500) results in a significant increase in the SNR (from 4.03 to 5.08), this is obviously not sufficient to provide significant changes in detection rate or detection time. For the detection time, it is the individual pair differences that have been statistically evaluated and not the difference between the median values. This is a strong indication that the detection time is only moderately changed. In contrast to this, the correction for the cochlea delay time (7CW500PC) leads to the expected further improvement in the SNR, in the detection rate, and in the detection time compared to the AM500 condition.

In an earlier publication (Stürzebecher et al, 2001), we found an SNR increase of about 60% using a so-called AM3MF2 multicarrier stimulus (three AM carriers with a distance of two times the modulation frequency between consecutive carriers) compared to the usual amplitude-modulated carrier. The present results show that this increase was somewhat overestimated at that time. The spectrum of AM3MF2 is comparable with the 7CW stimuli presented here, for which an SNR increase between 26% (500 Hz) and 42% (2000 Hz) was found compared to the usual amplitude-modulated stimulus. The SNR increase rises to 34% (500 Hz) and 55% (2000 Hz) through the introduction of the phase correction. In the previous publication, a small sample of 14 subjects was used. Due to the high between-subject variability, this small sample was not sufficient to make an accurate evaluation of the size of SNR increase. This is probably the reason for the slight overestimation of the SNR increase in the former study. The present investigation was carried out on a significantly larger sample (56–63 participants) to gain reliable information about efficiency for the new stimuli.

The additional introduction of a frequency offset for the 500 Hz stimulus (7CW500PC/FO) enables the use of a q-sample test for the response detection. This leads to a further improvement in the response detection at this low frequency. Thus, the detection rate with the new 500 Hz stimulus using the q-sample test lies at about the same order of magnitude as the detection rates for the new stimuli at the other frequencies (range 91% to 97%).

Similar to the improvement in detection rate, the median detection time was significantly reduced with the new stimuli; especially at 500 Hz and 4000 Hz. The differences between the median detection times become relatively small across the different frequencies (range 46–59 sec; NB: 26 sec for 1000 Hz). The only exception is at 1000 Hz, where the detection time is very short due to the large SNR. A relative uniform median detection time would be favorable if the different stimuli should be applied simultaneously in an ASSR-based multifrequency threshold test. In such a test, some of the savings in test time compared to testing one frequency at the time will be lost if there are large differences in the efficiency of the individual stimuli.

Although responses are detected within 100 sec in a high number of the recordings (about 77%), as shown in Figure 4, the distribution has a long tail that consists of about 18% of the recordings in which responses are detected after more than 100 sec and of an additional 5% of the recordings in which responses are not detected after 300 sec. All subjects in the present experiment had normal hearing, and with a stimulus level of 30 dBnHL, the goal would be to detect a response in all recordings within a given test time. There is, however, a large intersubject variability of the response amplitude and of the electrophysiological background noise level from which the response is extracted.

The reason for the present result, in which a response is detected within 300 sec in only 95% of the recordings, is probably related to a nonoptimal recording condition. The test subjects were encouraged to lie quietly and, if possible, to sleep during the investigation. However, many participants were not able to sleep, as indicated by entries into the test log made during each recording session. It is noted that a number of participants were restless, particularly during the final phase of the recording session. This creates difficult conditions for the electrophysiological recordings. The more restless the subject is, the poorer the SNR and the more difficult it is to detect a response within a given time window. At the low-stimulus level used in the present experiment, it will not be possible to detect a response if the degree of restlessness is too great.

For this reason, children should be examined during natural sleep or when lightly sedated. A greater SNR and thus a more favorable condition for the response detection in comparison to the awaking state arises in sleep, as a consequence of the lower amplitude of the electrophysiological background noise. Short response detection times can be expected with the new stimuli, even close to the threshold, if this requirement is fulfilled. There is also an additional factor to consider: namely, that most of the children to be investigated have a sensorineural hearing loss with recruitment. In these cases, it is relatively easier to detect a response near threshold.

Nevertheless, it is a problem to establish a specific time limit for recording a response to a specified stimulus level. The time limit selected in the present experiment (300 sec) may be too short for recordings close to the threshold in a child who is not sufficiently quiet. However, a maximum test time of more than 300 sec could lead to unacceptable prolongations of the total test session because at least one measurement below the threshold is necessary for each threshold evaluation.

An intelligent, automatic algorithm to control the maximum recording time, for example, depending on the time course of the statistical test value in a sequential test procedure, could provide a workable solution. The individual recording could be automatically continued if the statistical test value indicates a continuous rise during the sequential testing. If, for example, the statistical test value reached a response probability of 70% after the expiry of 300 sec, then the necessary time to reach the desired level of significance could be estimated and the test continued. In contrast, if the test value continues to move below a response probability of, for instance, 50%, the recording should not be continued after the maximum recording time has elapsed.

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