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The goal of the study was to investigate whether the temporal resolution of the auditory system is influenced by the variability of the stimulus envelope. To do so, the ability to detect an increment in the duration of a temporal gap (the test gap) was measured with an adaptive 3-IFC procedure. The stimulus consisted of a series of 10-ms broadband noise pulses. The pulses were separated by a 10-ms silent period, or temporal gap. In the main experiments, the test gap was either the first or the last gap in a series of 21 pulses. The variability in the stimulus' envelope was controlled directly by applying a jitter to the onset of the individual pulses in the pulse trains. Additionally, the stimuli were presented with different fine structure variabilities which also induced differences in the variability of the envelope. The gap-discrimination thresholds for the jittered noise pulse trains showed strong dependence on the amount of jitter as long as the jitter was applied randomly leading to a different pattern for every stimulus. When the jitter was applied as a frozen jitter resulting in a constant pattern of pulses, the thresholds did not increase significantly. A similar result was obtained for the different fine structure variabilities. A frozen fine structure led to thresholds about 1 ms lower than those obtained with random noise stimuli. A measure for the envelope variability was provided by calculating the variances of the envelope spectrum of the gammatone-filtered stimuli. The results of the calculations show a qualitative correspondence to the experimental results.

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INTRODUCTION

The processing of the temporal structures within acoustic signals by the human auditory system has long been a field of interest in perceptual investigations. The auditory system seems to have developed several different strategies to analyze the temporal properties of a signal. To improve the detection of long-duration signals it seems to be able to integrate information over a period of time with a typical duration of about 200 ms (e.g., Plomp and Bouman, 1959). In contrast to this integration process the ear can resolve acoustic events with a minimum temporal separation of a few milliseconds, as can be found in gap-detection or forward-masking experiments (e.g., Plomp, 1964; Penner, 1977). These two values represent upper and lower bounds of several other time intervals that have been deduced from experiments with nonstationary signals. A consistent theory that explains these various temporal factors has not yet been developed (e.g., de Boer, 1985; Green, 1985).

In contrast to the short time constants usually associated with temporal resolution, the results of some experiments indicate that the ear's judgment is based upon a long-term analysis of the temporal properties of the signal's envelope. Gap-detection and forward-masking experiments using narrow-band noises show that the inherent fluctuations of the noise may be confused with the gap or the signal and limit detection performance (Fastl and Bechly, 1981; Neff, 1985, 1986; Shailer and Moore, 1985).

In a narrow-band forward masking experiment, Neff (1986) observed that the signal was most difficult to detect if its duration corresponded to the most frequent intervals between minima in the envelope of the narrow-band noise masker. This means that the signal could be discriminated from the surrounding acoustical environment (the masker) more accurately if its temporal extent deviated sufficiently from the prominent periodicities in the background. Thus in this case of a narrow-band forward masker, the experimental paradigm changed from *detecting* a tonal signal to *discriminating* it from the preceding masker utilizing an analysis of the temporal structure of the stimulus.

The aim of the present study was to test the hypothesis that the listener's judgment in a temporal-resolution task can sometimes be based upon a (relatively) long-term analysis of the temporal structure of the stimulus.

Gap-discrimination experiments were used to test the listener's ability to analyze the temporal structure of a stimulus. The experiments were set up in such a way that the degree of temporal variability of the stimulus' envelope could be controlled without having to change the stimulus' bandwidth. In the main experiments, sequences of 21 white-

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noise pulses with 20 embedded gaps were used as stimuli. Gap-duration discrimination thresholds were measured for either the last or the first gap in the sequence. In the baseline condition, the pulses occurred at a fixed rate, which resulted in a pronounced peak in the spectrum of the stimulus' envelope. Temporal variability was then increased by jittering the temporal positions of the pulses by a certain amount. Since random noise shows inherent temporal variability in its envelope due to its random fine structure the experiments were performed for random-noise as well as for frozen-noise stimuli (explained in detail below) with the same overall bandwidth.

To allow a comparison of these experiments with previously published gap-discrimination studies (Abel, 1972; Penner, 1976; Divenyi and Danner, 1977) that used only two marker pulses, the following additional experiments were performed. First, it was investigated whether there is a difference in gap-discrimination thresholds between a gap bounded by only two noise markers and a gap embedded in the sequence of 21 pulses occurring at a fixed rate. Second, we examined whether the period of the pulse sequence or the duration of the reference gap itself determined the base duration for the discrimination judgment. Finally, since we used random-noise and frozen-noise stimuli in the central experiment, we investigated for the two-pulse and the 21-pulse conditions how the discrimination performance was influenced by different amounts of fine structure variability.

I. GENERAL METHOD

A. Procedure

In all experiments a 3-interval forced-choice (3-IFC) adaptive procedure was used to measure gap duration discrimination thresholds. A trial consisted of three intervals, with two intervals containing a stimulus with the reference test gap of duration T ms and a test interval where the test-gap duration was incremented by ΔT ms. If not stated explicitly, the reference gap duration was 10 ms. The presentation of the incremented gap was random with equal *a priori* probability for each observation interval. The subjects were asked to mark the interval containing the longest test gap. Feedback was given to indicate whether the response was correct or not. A two-down one-up decision rule determined the current value of ΔT. After each incorrect response ΔT was incremented by one step, after two consecutive correct answers at the same value of ΔT, ΔT was decremented by one step. This algorithm theoretically estimates the 70.7% point of the psychometric function (Levitt, 1971). Initial values for ΔT were set well above threshold. The initial stepsize of 4 ms was halved at every down-bound turn-around point. After the stepsize reached the final value of 0.25 ms, it was held constant for another 20 trials. Thresholds were determined by calculating the medians of the ΔT values during these last 20 trials.

B. Stimuli and apparatus

The noise used in these experiments was digitally generated in the frequency domain with a flat amplitude and a random phase spectrum between 20 Hz and 10 kHz (0.3-Hz frequency spacing). The noise was then inverse Fourier transformed and stored in a circular buffer (65536 samples). In the case of the random and the half-frozen noise (see below for further explanations) a new independent noise buffer was generated for each individual adaptive threshold estimate and for a trial or an interval a new noise sample was drawn from the circular noise buffer with a random onset. Prior to D/A conversion the noise was digitally multiplied by the appropriate temporal envelope to form the stimuli.

The signals were converted by a 16-bit DAC at a sampling rate of 20 kHz and low-pass filtered at 5 kHz with two low-pass filters in series, each with a steepness of 48 dB/oct. The spectrum level of the signal was 33 dB SPL/Hz corresponding to an overall level of 70 dB SPL for the continuous noise. The sounds were presented diotically via a Beyer DT 880 headphone set.

Each individual noise pulse had a rectangular envelope. As the noise carrier was digitally multiplied by the appropriate rectangular envelope before the low-pass filtering, the spectral shape of the spectral splatter produced by the onsets and offsets was also limited by the low-pass filter and was therefore inaudible. This prevented the listeners from using the splatter as an off-frequency cue to the onsets and offsets of the pulses. A similar method was used by Eddins *et al.* (1992) to limit spectral splatter for gap detection with narrow-band noise stimuli.

The basic signal configurations contained either two or 21 noise pulses with a duration of 10 ms each. The interpulse silent intervals within the signals had a duration of 10 ms leading to overall signal durations of 30 ms or 410 ms, respectively. The inter stimulus interval was 300 ms for the 21 pulse conditions and 680 ms for the two pulse conditions. In the measurements with the long pulse sequence the test gap was always the last gap in the sequence except in the last experiment.

C. Subjects

Three normal-hearing listeners including the first author took part in the present investigation. All subjects were highly experienced in psychoacoustical experiments. Before the collection of the data began, a substantial amount of practice was supplied until performance was stable. The duration of the training period differed among the three listeners and depended on the level of difficulty of the specific task, as well as the amount of experience in similar experiments. Generally each subject practiced between one and four hours per individual task until the performance appeared to be stable. The total amount of training could be as high as 30–40 h.

The subjects normally completed two experiments in parallel (e.g., for the last and the first gap in the sequence) before starting another experiment.

II. EXPERIMENT I: GAP DISCRIMINATION IN TRAINS OF TWO AND 21 PULSES

The first question in this investigation was whether gap-discrimination performance shows any difference for gaps that are bounded by only two marker pulses and for gaps that

TABLE I. Gap-duration discrimination thresholds for random-noise stimuli. Thresholds are given as the medians across four individual thresholds for each subject. Upper and lower quartiles are given in parentheses. The mean value is calculated across the three medians with standard deviation given in parentheses.

Subject	AS	MH	SM	Mean
2 pulses	1.19(1.06/1.38)	1.88(1.63/2.00)	2.00(1.75/2.13)	1.69(±0.44)
21 pulses	1.82(1.63/2.19)	2.25(2.19/2.38)	1.75(1.69/1.88)	1.94(±0.27)

are bounded by the last two pulses of a 21-pulse, 20-ms periodic pulse sequence. A random noise was used in both conditions.

A. Results and discussion

The medians of four gap-discrimination thresholds for each listener are shown in Table I together with upper and lower quartiles in parentheses. The column to the right gives the mean value across the individual thresholds with its standard deviation. The threshold values for the two conditions are always similar and do not differ markedly between subjects (with the exception of the rather low value for subject AS in the two-pulse condition). The average value for the two-pulse condition is 1.7 ms and the corresponding value for the pulse train is 1.9 ms.

Divenyi and Danner (1977) performed a gap discrimination experiment with two linearly gated noise markers (20-ms duration) where the gap had a duration of 5 ms between zero intensity points corresponding to a duration of 13.7 ms between half-intensity points. The thresholds for this condition were about 1 ms ($d'=1$) which is in good agreement with the results presented here. The thresholds in Divenyi and Danner (1977) and in this study are significantly lower than values of about 14.3 and 7.5 ms presented in earlier studies by Abel (1972) and Penner (1976), respectively (both using conditions identical to the two-pulse experiment presented here). Divenyi and Danner (1977) attributed their comparatively low thresholds to an intensive training over several months, and a similar argument can be used to explain our low thresholds. The value of training in temporal discrimination tasks is also demonstrated by results from a recent study by Fitzgibbons and Gordon-Salant (1994). They determined gap discrimination thresholds for ten young normal hearing subjects with only a minimal training of 2 h. The thresholds for a reference gap of 6.4 ms were about 12 and 17 ms for tonal markers of 500 and 4000 Hz, respectively.[1] These values are comparable to the results reported by Abel (1972) and even a factor of two higher than the values report by Penner (1976).

III. EXPERIMENT II: DETERMINATION OF THE BASE DURATION FOR THE DISCRIMINATION JUDGMENT

An important question in temporal discrimination investigations is what property of the stimuli defines the reference duration in the discrimination process. In the ''classical'' configuration with two markers bounding the gap, the gap duration T is likely to be the base duration. Abel (1972) and Penner (1976) presented data for a reference gap duration of 10 ms with marker durations of 10, 100, and 300 ms. The results did not show a significant dependence on the duration of the marker pulses. If, as assumed by Divenyi and Danner (1977), the onset–onset interval defined the reference duration, the thresholds would have increased markedly with the marker duration. If the observer's decision depended on the onset–onset interval as the reference duration in the case of the short pulses and on the gap duration in the case of the long marker signals, the thresholds would have been *lower* for long marker signals (provided the reference gap duration was the same in both conditions). This difference would have become more pronounced as the gap duration was decreased, relative to the marker duration. Since the thresholds in Abel (1972) and Penner (1976) showed no significant dependence on the marker-signal duration it can be assumed that the gap duration itself defined the reference duration in our experiments with two 10-ms marker signals.

In the case of the pulse trains, subjects may also choose the period of the sequence (20 ms) as the reference duration. This notion is supported by Neff's (1986) finding that the confusion of the signal with the narrow-band noise masker was most pronounced when the signal duration was similar to the mean period of the masker's envelope. This was also supported by the results of an earlier study by Neff (1985) where she tried to enforce confusion by using signals that were very similar to the pulse sequences we used here. A ''masker'' stimulus consisted of 19 identical 1-kHz sinusoidal pulses of 20-ms duration with a period of 20 ms. Another pulse identical to the preceding 19 pulses served as a ''signal.'' To enforce confusion the ''signal'' was present in all intervals and if its level was identical with that of the ''masker'' pulses, detection level was at chance. Neff could demonstrate that one potent cue to resolve confusion was to introduce a delay between the ''masker''-pulse sequence and the ''signal,'' thus introducing a deviation from the period in the stimulus. This is in essence the paradigm we use in the pulse-sequence configuration. The detection threshold for the presence of the delay in Neff's experiment was about 4 ms (Fig. 8 in Neff, 1985).

The following experiment was designed to determine the base duration that was extracted by the ear in both experimental situations investigated in the previous experiment. Gap discrimination thresholds were measured for different reference gap durations T, while the *period* of the pulse train was kept constant. This was done by adjusting the duration of the pulses so that pulse and gap durations always summed to the constant period of 20 ms. In the two-pulse conditions the ''period'' was defined as the duration between the onsets of the two pulses and the pulse duration was varied in the same way as for the pulse trains.

If the reference duration was the same for both stimuli then the dependence of thresholds on the gap duration should be the same for both conditions. If the period defined the reference duration then the thresholds should not vary with the gap duration since the period was always constant at 20 ms. If the gap itself defined the reference duration the thresholds should increase with increasing gap duration. Note that this line of reasoning does *not* require the Weber fraction $\Delta T/T$ to be constant. The only requirement here is that the

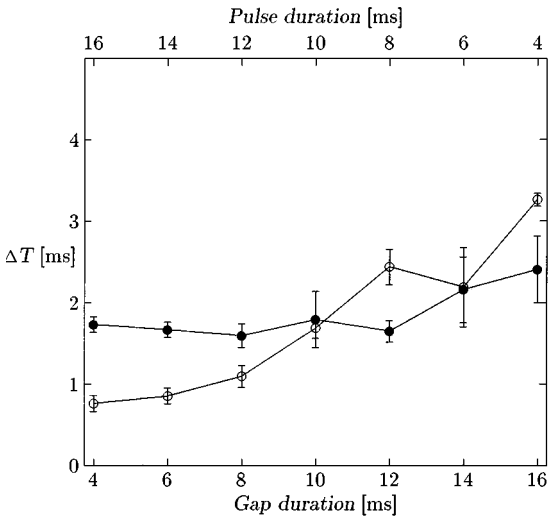

FIG. 1. Gap-duration discrimination thresholds for stimuli containing two or 21 noise pulses as a function of interpulse gap duration. The results for two pulses are depicted by the open circles and the results for 21 pulses are depicted by the filled circles. Standard deviations are indicated by error bars. The upper abscissa indicates the pulse duration.

discrimination thresholds *increase* monotonically with increasing reference duration and are *not* constant so that different reference durations yield different discrimination thresholds.

A. Experimental conditions

The apparatus and the subjects were identical to those of the first experiment. The stimuli were presented with seven different gap durations (4, 6, 8, 10, 12, 14, 16 ms). For each reference-gap duration thresholds were measured for a pulse train of 21 pulses and a single gap marked by two noise pulses. Random noise stimuli were used throughout the experiment.

B. Results and discussion

Figure 1 shows the gap discrimination thresholds ΔT as a function of the gap duration for the two-pulse (open symbols) and the pulse-sequence conditions (filled symbols). The data in the figure represent the mean values of the medians of the three subjects.

The thresholds for the two-pulse condition increase markedly with the gap duration, being 0.8 ms at a gap duration of 4 and 3.2 ms at a gap duration of 16 ms. Apart from the result for a gap duration of 14 ms the thresholds increase monotonically with increasing gap duration.

A linear-regression fit to the data for the two pulse condition yielded a slope of 0.20 and an intersection with the y axis at -0.24 ms. The slope is significantly different (t-test) from 0 ($p<0.0001$) whereas the intersection value is not significantly different from zero ($p>0.1$). Thus we may as well force the fitted line to go through the origin, which leads to a slope of a linear regression fit of 0.18.

The ΔT values for the pulse train are much less dependent on the gap duration and increase from 1.8 ms at the shortest gap to 2.4 ms at the longest gap. The slope of the linear regression fit, taken over all data, is 0.06 (intersection with y axis at 1.28 ms). This slope is significantly different ($p<0.0001$) from the slope of the two-pulse data, and also from a slope of zero ($p<0.0001$).[2] The slope of the linear regression fit for gap durations of 12 ms or less does not differ significantly from zero ($p>0.5$).

Based on the assumption that different reference durations should yield different discrimination thresholds it appears from the data that indeed two different base durations are used in the two conditions. For the two-pulse condition it is the duration of the gap between the two markers. For the pulse sequence for gap durations up to 12 ms the period is likely to be the base duration since the slope of the regression fit does not significantly differ from zero.

For larger gap durations a statistically significant increase with gap duration is present in the data for the pulse sequences although the slope still differs from that in the two pulse conditions. The subjects reported that for these pulse durations the task became more difficult because the pulse sequences sounded more variable due to the fact that the individual pulses were very faint.

TABLE II. Variability of the pulse-pattern fine structure. The letters indicate whether the fine structure of the signals is the same (S) or different (D) between individual runs, trials, intervals, or pulses in a signal.

	Run	Trial	Interval	Single pulse
Frozen-identical	S	S	S	S
Frozen	S	S	S	D
Half-frozen	D	D	S	D
Random	D	D	D	D

IV. EXPERIMENT III: EFFECT OF FINE STRUCTURE VARIABILITY ON DISCRIMINATION PERFORMANCE

Random noise contains inherent envelope fluctuations caused by fine structure variations. Because such fluctuations could influence temporal discrimination performance, we used both random *and* frozen noise stimuli in the main experiments (experiments IV and V). This allowed us to separate the influence of inherent fluctuations from the variations we introduced by jitter. To investigate the continuum between random and frozen fine structures used in the main experiments, two additional fine structures were studied in the following experiment. Because there was no gap discrimination study available in which fine structure variability was manipulated, the experiment was carried out both for stimuli containing 21 pulses and stimuli containing two pulses.

A. Experimental conditions

Apart from random noise, three additional fine structure variabilities were used in this experiment. An overview of the different variabilities is given in Table II.

The first one, with the lowest level of variability, is what we call a frozen-identical noise pulse train. A fixed 10-ms sample of noise was used to generate all signals. Each individual noise pulse in every presentation of the signals was identical to every other noise pulse. Thus the signal consisting of 21 frozen-identical noise pulses was completely peri-

TABLE III. Individual and mean gap-duration discrimination thresholds for the two and the 21-pulse condition for random, half-frozen, frozen, and frozen-identical fine structure. The results for random noise are replicated from Table I. Upper and lower quartiles and standard deviations are indicated in parentheses. In the right column the means pooled over all subjects and the two and 21-pulse conditions for each fine structure variability are given (standard deviations are indicated in parentheses).

Subject		AS	MH	SM	Mean	Pooled
Frozen-identical	2	0.50(0.44/0.63)	1.25(1.00/1.63)	1.25(1.13/1.38)	1.00(±0.43)	1.02(±0.29)
	21	1.00(0.94/1.00)	1.19(1.06/1.38)	0.94(0.81/1.00)	1.04(±0.13)	
Frozen	2	0.88(0.81/0.94)	1.00(0.75/1.25)	1.50(1.44/1.63)	1.13(±0.33)	1.23(±0.33)
	21	0.94(0.88/1.31)	1.63(1.38/1.75)	1.44(1.13/1.69)	1.34(±0.36)	
Half-frozen	2	0.88(0.75/1.19)	1.75(1.63/1.88)	1.63(1.25/1.75)	1.42(±0.47)	1.75(±0.62)
	21	2.00(1.75/2.00)	2.75(2.63/2.88)	1.50(1.44/1.88)	2.08(±0.63)	
Random	2	1.19(1.06/1.38)	1.88(1.63/2.00)	2.00(1.75/2.13)	1.69(±0.44)	1.82(±0.35)
	21	1.82(1.63/2.19)	2.25(2.19/2.38)	1.75(1.69/1.88)	1.94(±0.27)	

odic. It showed a pronounced line spectrum with the line separation of 50 Hz corresponding to the repetition rate of the pulses within the trains. This stimulus was used later in the main experiments.

The second fine structure variability was called frozen-noise pulse train. We took 21 independent noise pulses of 10-ms duration to generate the pulse trains. These 21 noise pulses were used in every signal presentation. Every pulse within a signal differed from every other pulse in the sequence, but the sequence was identical across intervals and trials. The last two pulses bounding the test gap in the pulse-train situation were identical to the marker pulses in the two-pulse condition.

The third fine structure variability we introduced was what we call a ''half-frozen'' noise. Within one trial, the variability was identical with a frozen noise, i.e., every pulse within a signal was identical to the corresponding pulse in the two other intervals. In contrast to frozen noise, a different set of noise pulses was presented in every trial of a run. This prevented the subjects from becoming familiar with a specific sequence.

The three fine structure variabilities were tested in both situations: two and 21 noise pulses. All other experimental parameters were identical with those used in experiment I.

B. Results and discussion

The individual results presented in Table III are given together with means across the three listeners. For each fine structure variability the differences between the 2- and 21-pulse conditions are statistically insignificant on a 5% level (one sided student t test). Thus the pooled means for each fine structure variability are also given. In general the gap-discrimination thresholds increase with increasing variability. The lowest thresholds are about 1 ms for the frozen-identical condition and they increase to nearly 2 ms for the random-noise stimuli.

Random variations of the fine structure either between intervals (random) or between trials (half-frozen) yield mean thresholds in the range of 1.4 to 2.1 ms. The subjects reported that in these two conditions the sharpness of the onsets and offsets of the marker pulses varied strongly although the gaps were always audible. Thus the temporal extent of the gap was not as clearly defined as in the frozen-identical and frozen-noise conditions. Although in the half-frozen noise condition the signals were directly comparable within one trial, this did not improve the mean thresholds compared with the random noise situation.

A constant fine structure throughout the experiment led to thresholds of about 1 ms (frozen and the frozen-identical situation). One might argue, that in the 21-pulse condition with frozen-identical pulses, the very low thresholds might have been based on a spectral rather than a temporal cue. A deviation of the regularity of the sequence introduces a disruption of the pronounced line spectrum of that signal which might have served as the detection cue. However, the comparable magnitude of the thresholds for frozen *and* frozen-identical pulse trains supports the view that such a spectral cue is not necessary to reach these low thresholds. This result indicates that it is not the simple structure of the spectrum but rather the long-term constancy of the temporal pattern that enhances the performance in these conditions.

These observations are supported by a statistical analysis of the pooled means which reveals significant differences between the following pairs of variability conditions: frozen-identical versus random ($p<0.005$), frozen versus random ($p<0.025$) and frozen-identical versus half-frozen ($p<0.05$). The differences between adjacent pairs are not significant: frozen-identical versus frozen ($p>0.1$), half-frozen versus random ($p>0.1$) and frozen versus half-frozen ($p>0.05$). This statistical analysis suggests that, indeed, the stimuli used in the experiment represent a continuum in the increase in variability from frozen-identical to random noise.

As we have seen, gap-discrimination thresholds are sensitive to fine structure variability. These variations in fine structure lead to higher thresholds if they vary throughout the experiment because they disturb the temporal constancy of the signals. Since the envelope depends on the fine structure of the signal, the increase in thresholds with increasing fine structure variability can be also attributed to the resulting increase in envelope variability. The influence of inherent envelope fluctuations of narrow-band noise on gap *detection* has been discussed by several authors (Eddins *et al.*, 1992; Shailer and Moore, 1983, 1985). It is likely that the same fluctuations have an influence on gap *discrimination* as well.

V. EXPERIMENT IV: GAP DISCRIMINATION IN JITTERED NOISE PULSE TRAINS

The goal of this and the following experiment was to test the hypothesis that under certain experimental conditions the auditory system bases its judgment in temporal resolution tasks on a relatively long-term analysis of the stimulus' temporal structure. Normally these conditions occur in experiments with narrow-band noise stimuli where a gap or a signal can be confused with the inherent envelope fluctuations of the noise. To vary the temporal variability of the envelope in these experiments one has to vary the bandwidth of the stimuli. Thus the resulting influence on the threshold can be either due to the variation in overall bandwidth or to the different temporal variability. To separate the influence of the temporal variability from changes in overall bandwidth we used broadband noise pulse trains, where temporal variability was introduced by jittering the positions of the noise pulses. In this way the temporal variability could be controlled without changing the overall bandwidth of the stimulus. As in the previous experiments, the test gap was the last gap in a sequence of 21 noise pulses in order to allow an investigation of the long-term effect of the whole stimulus preceding the test gap.

As we have seen in the experiments I–III, the inherent fluctuations of the noise pulses influence the gap-discrimination thresholds. To differentiate between the inherent temporal variability and the variability introduced by the jitter, the experiments were performed using frozen-identical noise as well as random-noise stimuli. All following experiments were performed for pulse trains of 21 pulses.

A. Experimental conditions

The baseline stimulus was a periodic noise pulse train as used in the experiments I–III. The jitter was only applied to the onset time of the pulses. The duration of the pulses was always 10 ms. To generate jittered pulse trains we used the following equation to determine the onset time T_i of the ith pulse:

$$T_i=(i-1)T_0+j_iJ_{\max}, \tag{1}$$

here T_0 denotes the unjittered pulse period of 20 ms and $J_{\max}$ is the maximum possible jitter or jitter amplitude. $J_{\max}$ was varied from 0 to 4 ms. The j_i were selected randomly from a uniform distribution between $+1.0$ and -1.0. The position of the first pulse in a train, as well as the position of the pulses bounding the test gap, were never subjected to jitter. There were two reasons for this: first, the test gap should have the same duration of 10 ms in all reference presentations so that it was only altered in duration by introducing the increment ΔT, allowing a direct comparison with the test interval. Second, the average gap duration within the signals as well as the total signal duration were kept constant with this method.

The jitter was applied with two different levels of variability. ''Random jitter'' denotes the condition where the set of random numbers j_i was independent for every interval. For ''frozen jitter,'' one set of random numbers j_i was chosen and applied identically in all intervals of the corresponding measurements. This set of random numbers was the same for all values of $J_{\max}$. Thus in the frozen-jitter condition the pulses occurred at irregular time points but with the same irregular time pattern in all intervals of all runs.

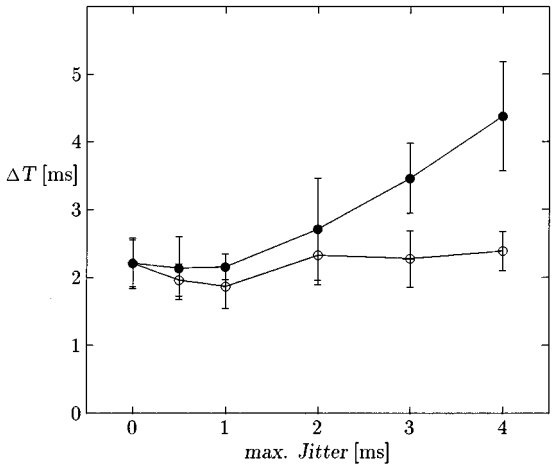

FIG. 2. Gap-duration discrimination thresholds for a test gap position at the end of a noise pulse sequence with a random fine structure. The abscissa indicates the jitter amplitude. Open symbols denote frozen jitter and filled symbols random jitter. Each data point represents the mean over the medians of three subjects. Standard deviations are indicated by error bars.

These two different jitter conditions were combined with two fine structure variabilities, namely frozen-identical and random fine structure, giving altogether four different experimental conditions.

B. Results and discussion

The performance across the subjects was sufficiently similar that we present means of the results together with the standard deviations indicated as error bars. The results are presented in Fig. 2 for the random-noise fine structure and in Fig. 3 for the frozen-identical fine structure.

Thresholds for the random noise with a random jitter (filled symbols in Fig. 2) show an increase with increasing jitter amplitude from 2.25 to 4.25 ms. Surprisingly, the thresholds for the frozen jitter show no dependence on the

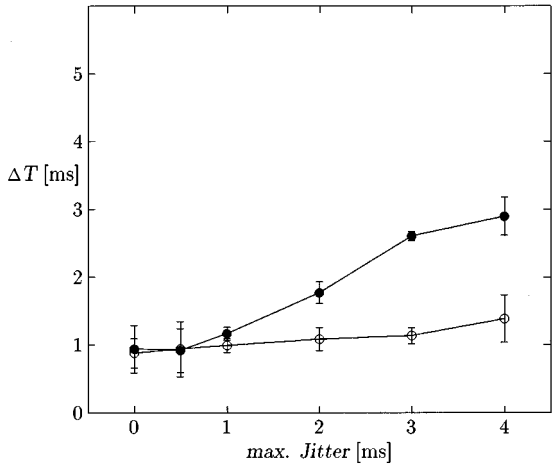

FIG. 3. Same as in Fig. 2, but for frozen-identical noise bursts.

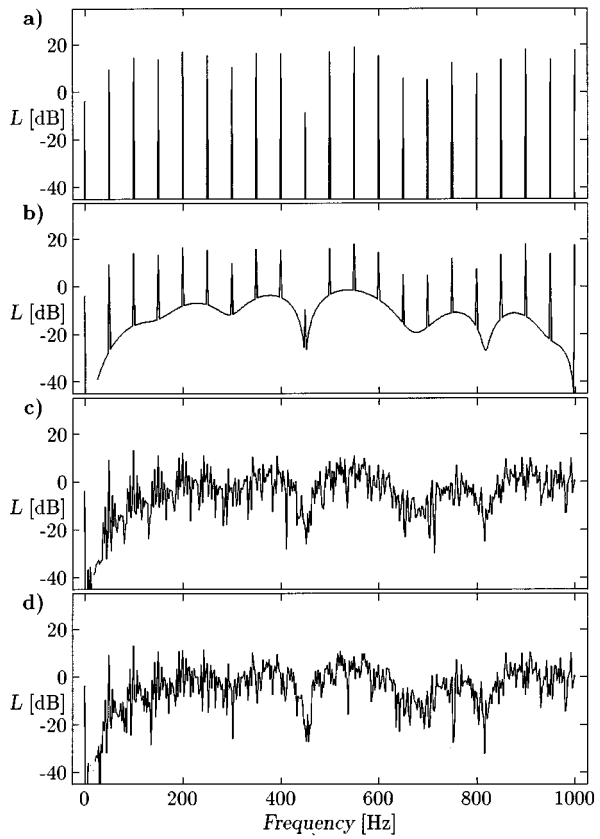

FIG. 4. Comparison of power spectra (between 0 Hz and 1 kHz) for some of the stimuli used in the experiments. Panel (a): Power spectrum of the periodic frozen-identical pulse pattern. Panel (b): Power spectrum of a periodic frozen-identical pulse pattern with an increase of 1 ms (threshold value) in the duration of the last gap. Panel (c): Power spectrum of a frozen-identical pulse sequence with a jitter of 2 ms. Panel (d): Power spectrum of a frozen-identical pulse sequence with a frozen jitter of 2 ms with an increase of 1 ms (threshold value) in the duration of the last gap.

jitter amplitude. The thresholds are constant at about 2.25 ms. The trend in the results for the frozen-identical fine structure (Fig. 3) is almost identical to that for the random noise. Thresholds for the random jitter show a clear dependence on the jitter amplitude, whereas the thresholds for the frozen jitter do not seem to be affected by the jitter and are nearly constant around a value of 1 ms. The only difference between the two fine structure variabilities is an offset of about 1.25 ms for the random-noise situations with respect to the corresponding frozen-identical situations. This result is consistent with the results from experiment III.

Frozen jitter seems to have no effect on the thresholds for either noise fine structure variability. Even a jitter amplitude of 4 ms does not increase the gap discrimination threshold significantly. This result is especially interesting in the case of the frozen-identical fine structure. It confirms the previous conclusion from experiment III that the low thresholds for these signals are not primarily a consequence of spectral characteristics. The line structure of the spectrum of the periodic frozen-identical pulse train is heavily disrupted by the temporal jitter, so that the increment in gap duration introduces a negligible deviation from the spectrum. This can be demonstrated in Fig. 4. The upper panel shows part of the power spectrum of a completely periodic frozen-identical pulse train. Panel (b) shows the spectrum for the corresponding signal with an increase in the test-gap duration of 1 ms (threshold value). Panel (c) shows the spectrum of a frozen-identical pulse train jittered with 2 ms and no increase in the test-gap duration. Finally, panel (d) shows the spectrum of a frozen-identical pulse sequence with a jitter of 2 ms and an increase in the test-gap duration of 1 ms (threshold value). For the frozen-identical noise, the jitter itself clearly disturbs the spectrum more than the 1-ms increase in gap duration. It seems that the temporal constancy of the pattern itself throughout the experiment is the major factor in the enhancement of the temporal discrimination performance.

With the random jitter, the thresholds show a strong dependence on the jitter amplitude for both fine structure variabilities (Fig. 2 and Fig. 3). Both threshold curves show nearly the same monotonic increase from no jitter to a maximum jitter of 4 ms. At a jitter amplitude of 4 ms, thresholds are increased for both curves by about 2 ms compared with the no-jitter condition.

It is important to note that the duration of the test gap was never affected by the jitter and was only incremented by ΔT in the test intervals. Therefore, subjects could have made a direct comparison of the test gap in the reference and the test intervals. If the auditory analysis interval had been restricted to the duration of the test gap and the two noise bursts immediately preceding and following the test gap—a short-term analysis over 30 ms—then the thresholds would not have been influenced by the jitter. To explain the increase of discrimination thresholds one needs a longer analysis interval which covers at least a few of the 19 preceding gaps in the sequence. So far the results support the notion of a long-term analysis in connection with this temporal resolution experiment.

VI. EXPERIMENT V: TEST GAP AT THE BEGINNING OF THE SEQUENCE

It seems reasonable to expect that the confusion effects Neff (1986) reported for forward masking conditions with narrow-band noise maskers could also occur in parallel backward masking conditions. This would mean that portions of the stimulus *following* the signal are included in the analysis. In a similar manner, for our conditions, we could expect that trailing information would affect the detectability of the test gap at the beginning of the pulse sequence. To test this hypothesis, the test-gap was presented at the beginning of the sequence in the following experiment.

A. Experimental conditions

In this last set of experiments the test gap was positioned at the beginning of the 21-pulse sequence so that the jittered part of the sequence *followed* the test gap. All other parameters were identical to those used in experiment IV, except that in the case of the frozen jitter the set of random numbers that determined the jitter was different.

B. Results and discussion

The results are presented in Fig. 5 for the random noise and in Fig. 6 for the frozen-identical noise pulse sequences.

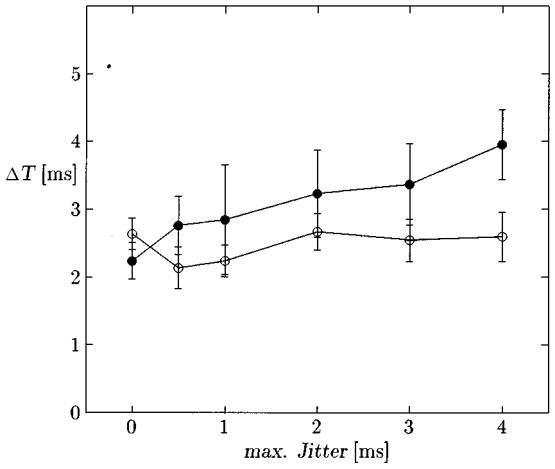

FIG. 5. Same as in Fig. 2, but for test gaps at the beginning of a random-noise pulse sequence.

The results for the frozen jitter and random jitter conditions are represented by open and closed symbols, respectively. The symbols denote mean values across three subjects with standard deviations indicated as error bars. The results for the random noise with a frozen jitter show a roughly constant discrimination threshold of about 2.5 ms. The threshold curve for the random jitter increases with jitter amplitude to a maximum value of about 4 ms. The trend in the thresholds for the frozen-identical noise is the same except for the absolute values. For the frozen jitter the thresholds stay constant around 1.5 ms and the random jitter elevates the thresholds to a maximum of 3 ms at the 4-ms jitter amplitude.

Thresholds for the periodic sequences (0-ms jitter amplitude) tend to reach higher ΔT values compared with the experiments where the test gap was presented at the end of the pulse trains. The differences in thresholds are about 0.25 ms for the random noise and 0.5 ms for the frozen-identical noise conditions. As in the previous set of experiments the frozen jitter did not affect the discrimination thresholds for both fine-structure conditions and the thresholds again depended on the jitter amplitude when the jitter was randomized. Though the slopes of the curves for the random jitter situations were a bit steeper when the test gap was positioned at the end, there is no obvious qualitative difference in the results for the two test gap positions. This leads to the conclusion that information about the temporal structure of the signals preceding as well as following the test gap is incorporated in this temporal analysis process.

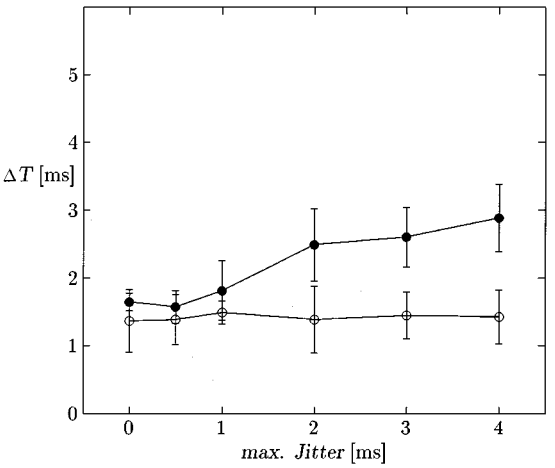

FIG. 6. Same as in Fig. 5, but for frozen-identical noise bursts.

VII. CALCULATION OF THE ENVELOPE VARIABILITY

So far our interpretation of the results leads to the notion that fluctuations in the envelope due to either fine structure variability or jitter increase the gap-discrimination thresholds. The question now is how to obtain an appropriate measure for the variability of the envelope of the stimuli. Several earlier studies have mentioned and/or calculated quantities that were derived from the envelopes of the stimuli (e.g., Martens, 1982; Hartman and Pumplin, 1988; Richards, 1992; Green *et al.*, 1992; Bernstein and Trahiotis, 1994). Our approach comes probably closest to the approach of Green *et al.* (1992), who considered the mean power spectrum of the envelope and the standard deviation for each component in this spectrum. Our calculations are intended to provide a measure of stimulus variability and are not intended to yield quantitative predictions of thresholds. That would require the inclusion of an internal noise source and a reasonable decision device, both of which are beyond the scope of this study.

In order to obtain a measure for the variability introduced by different forms of jitter and fine structure, the following approach was used. First, the filtering in the inner ear was simulated with a gammatone filterbank (Patterson *et al.*, 1987). The gammatone filters covered a range of center frequencies from 124 to 4470 Hz yielding altogether 25 filtered signals. Then, for the output of each gammatone filter, the amplitude spectrum of the envelope was determined for envelope frequencies up to 1000 Hz. For simplicity, we will use the term envelope spectrum for this amplitude spectrum of the envelope. This calculation was performed for 200 independent representations of the reference stimuli used in experiment IV (test-gap duration at 10 ms). From these 200 spectra, the mean envelope spectrum was then calculated together with its variance. The variances for the mean envelope spectrum in one gammatone filter were then averaged across envelope frequency to obtain a measure of variance for this filter. The resulting variances for all 25 gammatone filters were then averaged across filters to yield an overall measure for the variability of the stimulus (see the Appendix for further details).

The results are shown in Fig. 7 as mean variances for maximum jitter values of 0, 1, 2, 3, and 4 ms for the four different fine structure/jitter combinations (for the scaling and the units of the mean variances see the Appendix).

For the frozen-identical noise with frozen jitter (open squares) the mean variance is zero since all 200 representations of the stimuli were identical. In this case the internal noise limits the performance of the auditory system. The mean variance for the random noise with frozen jitter (closed squares) is almost independent of the maximum jitter and shows values of about 0.03. For the random jitter the vari-

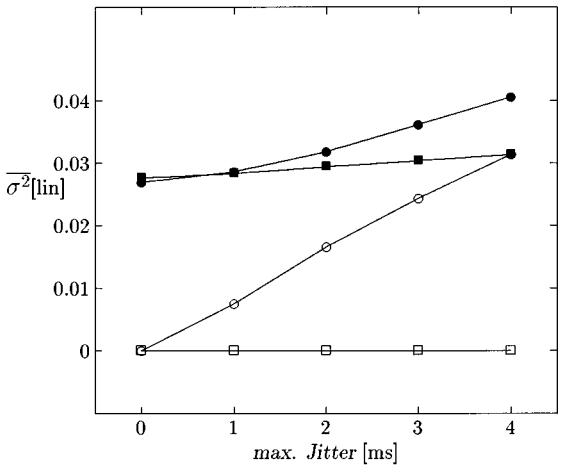

FIG. 7. Averaged envelope spectrum variances $\overline{\sigma^2}$ over maximum jitter for different fine structure and jitter variabilities. $\overline{\sigma^2}$ is given in linear units and can be regarded as being proportional to either V^2 or Pa^2. Frozen-identical noise with frozen jitter (□), frozen-identical noise with random jitter (○), random noise with frozen jitter (■) and random noise with random jitter (●). Stimuli were the reference stimuli (no increase in the duration of the last gap) of experiment IV. See text for details of the calculation.

ability in the envelope increases markedly for both fine structures with increasing jitter amplitude. For a random noise a random jitter (closed circles) of 4 ms produces a mean variance of 0.042. For the frozen-identical noise (open circles) this jitter amplitude yields a mean variance of 0.032.

An important point in the results shown in Fig. 7 is that the mean envelope spectrum variance for frozen-identical noise stimuli with a random jitter of 3 ms approaches the mean envelope spectrum variance for *periodic* random noise stimuli. This is similar to the experimental result that a random jitter of 3 ms is needed for the frozen-identical noise pulse trains to elevate the gap discrimination thresholds to the level of the periodic random noise stimuli (compare Fig. 2 with Fig. 3). Furthermore it is clear that the random noise fine structure itself leads to a substantial increase in the value of the mean variance compared with a frozen noise.

The main contributions for the increase in variance due to jitter come from envelope frequencies that are close to the frequency corresponding to the period of the sequences and its harmonics. Furthermore the mean-to-sigma *ratio* is much higher at the period frequency and its harmonics compared with a flat mean-to-sigma background at other frequencies (see the Appendix for details). This supports the notion that the period may play a special role by providing the base duration for the detection process for the pulse sequence stimuli.

Overall, the results of the calculations show a qualitative correspondence to the experimental results and support the view that gap discrimination thresholds are mainly influenced by envelope fluctuations induced by jitter and by fine structure variability.

VIII. SUMMARY AND GENERAL DISCUSSION

The experiments presented in this study were designed to investigate the possible influence of long-term signal parameters, such as fine structure fluctuations and envelope variability, on temporal resolution in the auditory system.

The results of the experiments showed that the temporal discrimination thresholds were affected by fine structure variabilities; increased variability led to increased thresholds. By comparing thresholds for signals with two pulses and for a sequence of 21 noise pulses we could demonstrate that the *period* of the regular pulse trains determined the reference duration for the auditory system, while discrimination in the two-pulse condition was determined primarily by the gap duration. The conclusion that the period was the base duration in case of the pulse sequences was also supported by results of calculations presented in the Appendix.

In the main experiments, the regularity of the noise pulse trains was disturbed by applying a jitter to the temporal positions of the individual pulses. This jitter was either varied randomly from interval to interval or was kept fixed for all intervals. As long as the pattern was kept fixed, the discrimination thresholds did not significantly increase due to the jitter. In the case of the *randomized* patterns, discrimination thresholds increased with increasing jitter. The effects due to jitter were nearly the same regardless of whether the test gap was placed at the beginning or at the end of the pulse trains. These findings are consistent with the conclusion that the discrimination of temporal gaps is based on a relatively long-term analysis of the signal envelope. This analysis appears to incorporate preceding as well as following portions of the signal and is affected by *random*, but not fixed, variations in the temporal pattern.

A quantitative measure of envelope variability was derived using a bank of gammatone filters. The obtained averaged variances depended in a similar way on the parameters of the experiments as did the behavioral data. In particular, the averaged envelope spectrum variance for a frozen-noise pulse train with a random jitter of 3 ms corresponded well with the value for a random noise pulse train without jitter, in agreement with the results of experiments IV and V.

The results of this study support the view that temporal-resolution experiments using narrow-band noise stimuli are significantly influenced by inherent fluctuations of the envelope (Neff, 1986). According to the results presented in this study, it should be possible to find gap detection thresholds for narrow-band frozen noises that are considerably lower than for random noise stimuli. We would expect that, under such conditions, the thresholds should be much less influenced by the signal's bandwidth. Thus far studies showing effects of bandwidth have only used random-noise signals (Shailer and Moore, 1983; Eddins *et al.*, 1992).

The experiments presented in this study do not allow us to assess the duration of the analysis window used by the auditory system. To investigate this duration, we are currently conducting experiments in which only a part of the sequence is jittered. The interpretation that the influence of jitter in a temporal-resolution task is due to the listeners performing a relatively long-term analysis of the stimulus might help to resolve contradictions described in previous studies. It is often the case that short time constants are found in temporal resolution (or temporal acuity) experiments and long time constants are found in test-tone integration experi-

ments (Green, 1985; de Boer, 1985). If the ear analyzes the signals on a rather long-term basis which enables it to either perform a time-intensity trade or a temporal resolution task, then there is no contradiction. Of course a model to describe these two properties of the auditory system could not in this case be based on the use of a simple integration process incorporating just one time constant.

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APPENDIX

To obtain a measure for the envelope variability the 420-ms long signals were first processed through a gammatone filterbank (Patterson *et al.*, 1987) to simulate peripheral filtering. Then, the envelope was calculated via the Hilbert transform by utilizing the outputs of each of the filters and their respective outputs shifted 90 deg in phase. The magnitude of this signal was then Fourier transformed and the amplitude spectrum up to 1 kHz was derived. This calculation was carried out for 200 independent examples of the stimulus. For these 200 spectra, the mean value and the variance of each component were determined. The variance was then averaged across envelope frequencies for one gammatone filter. This calculation was repeated for all 25 gammatone filters whose center frequencies ranged from 124 to 4470 Hz (corresponding to a range from 4 to 28 ERB). These 25 values were then averaged across all gammatone filters to give an overall estimate of the envelope variability. The measures concerning envelope spectra contain a constant scaling factor that incorporates the length of the Fourier transform and the amplitude scaling required for the digital signals to produce the correct sound level at the earphones (the measures of variance contain the square of this factor). It affected the absolute values of the estimates, but because it was the same for all conditions the relations between the results among the conditions are independent of this factor. The unit for the magnitudes can be regarded as being proportional to V or Pa, and for the mean variance the square of these, respectively.

The mean envelope spectra for four different stimuli calculated for the gammatone filter centered at 4470 Hz are shown in Fig. A1. Panel (a) displays the mean envelope spectrum for a periodic frozen-identical noise pulse train and shows the pronounced line spectrum as can be expected from the spectrum in Fig. 4 [panel (a)]. In panel (b) the mean envelope spectrum of a frozen-identical noise pulse train with a random jitter of 3 ms is shown. The jitter smeared out all of the envelope harmonics above 50 Hz. The 50-Hz component corresponding to the period of the stimulus can still be clearly distinguished in this envelope spectrum. Around

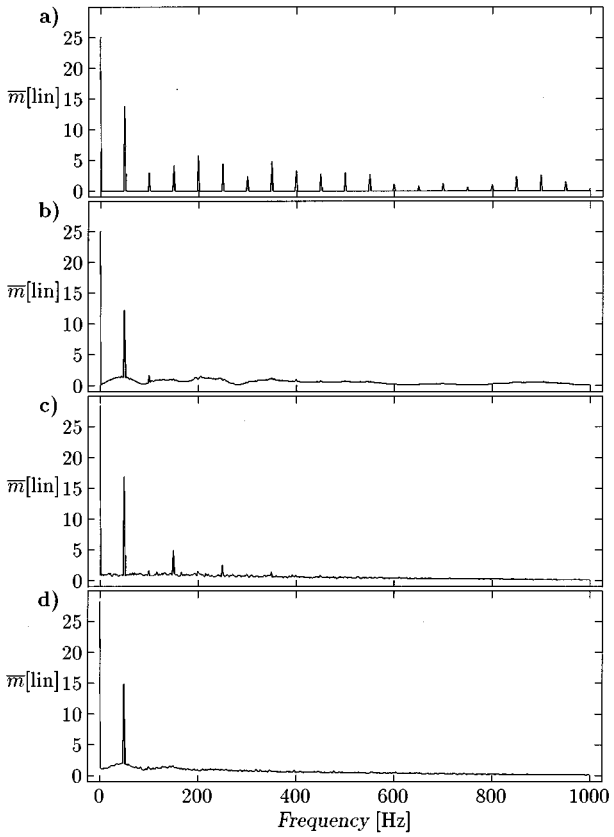

FIG. A1. Mean amplitude spectra of the envelope for different fine structure and jitter variabilities calculated for a gammatone filter centered at 4470 Hz (28 ERB). Panel (a): frozen-identical noise without jitter. Panel (b): frozen-identical noise with random jitter of 3 ms. Panel (c): random noise without jitter. Panel (d): random noise with a random jitter of 3 ms. Stimuli were the reference stimuli (no increase in the duration of the last gap) of experiment IV.

50 Hz a background ''noise'' has been built up by the jitter. Panel (c) depicts the mean envelope spectrum for a periodic random noise pulse train which shows only two clearly distinguishable periodicities in its spectrum namely at 50 and at 150 Hz. Finally, panel (d) shows the mean envelope spectrum for a random noise with a random jitter of 3 ms. Again the jitter smeared out all harmonics in the spectrum above 50 Hz.

The corresponding variances for the mean spectra shown in Fig. A1 are depicted in Fig. A2. The variances for the periodic frozen-identical noise pulse train are essentially zero [panel (a) in Fig. A2]. In panel (b) the variance shows maxima around the harmonics of 50 Hz which corresponds to the smearing out of the peak in the mean spectrum. The averaged variance for this spectrum [panel (b) of Fig. A2] has a value of 0.0973. Both frozen-identical noise stimuli do not show a variance in their 0-Hz component since the overall energy of the stimuli was not altered by the jitter.

The variance of the envelope spectra for the periodic random noise pulse train [panel (c)] shows no pronounced peak or maximum, but rather a sort of noise floor throughout the spectrum. The mean variance for panel (c) of Fig. A2 is 0.0976 which is in very good agreement with the value for the frozen-identical noise pulse train with a random jitter of 3 ms. This finding is also reflected in the overall variance

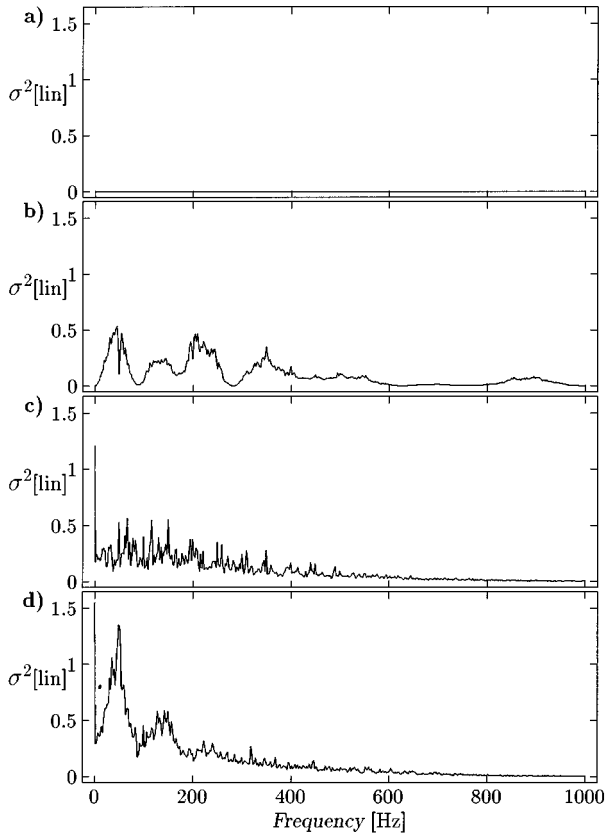

FIG. A2. Variances σ^2 for the mean spectra shown in Fig. A1. Panel (a): frozen-identical noise without jitter. Panel (b): frozen-identical noise with random jitter of 3 ms. Panel (c): random noise without jitter. Panel (d): random noise with a random jitter of 3 ms. Stimuli were the reference stimuli (no increase in the duration of the last gap) of experiment IV.

calculated over 25 gammatone filters (Fig. 7). Finally, the variance for the random noise with a random jitter of 3 ms [panel (d)] shows a similar pattern as for the frozen-identical noise pulse train. In this case the variance introduced by the jitter is more or less added upon the variance introduced by the fine structure. The averaged variance for this stimulus is 0.1494.

An interesting property of rectangularly modulated random noise can be derived by comparing panels (c) in Fig. A1 and Fig. A2. Green *et al.* (1992, Fig. 1) pointed out that, for a Gaussian noise with a rectangular spectrum, the relation between mean and sigma of envelope power is approximately 1. This is a general property of a bandpassed Gaussian noise, because each line in the envelope power spectrum is exponentially distributed. Green *et al.* (1992) supported this analytical property by numerical simulations, in which they also showed that, for equal-amplitude noise, the ratio between mean and sigma of envelope power is about 10% larger than the ratio for Gaussian noise. Since we based our estimates on the *amplitudes* of the spectral components of the envelope (and not on their *powers*, as did Green *et al.*) the theoretical mean-to-sigma ratio of our estimates is 1.91 for Gaussian noise (not 1). This number is derived from the fact that the *amplitudes* in the envelope spectrum are Rayleigh distributed. Given that we used equal-amplitude noise, consisting of many more components per band than the

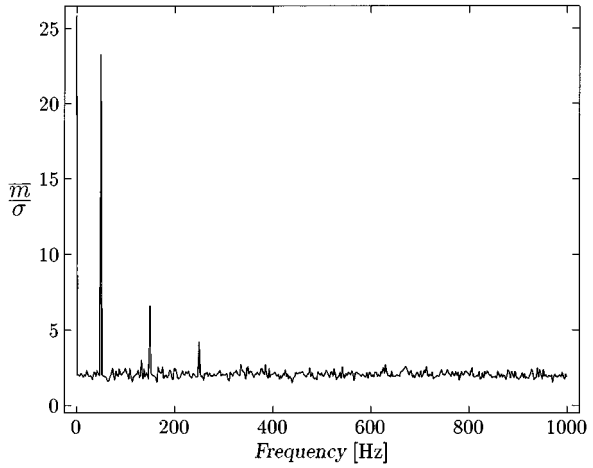

FIG. A3. Mean-to-sigma ratio derived from the panels (c) of Fig. A1 and Fig. A2.

equal-amplitude noise used by Green *et al.*, we expected (by analogy with the simulations performed by Green *et al.*) a mean-to-sigma ratio slightly above the theoretical value of 1.91 for Gaussian noise.

As shown in Fig. A3, our calculations reveal mean-to-sigma ratios that are much larger than 1.91 at those envelope frequencies that correspond to odd-order harmonics of the 50-Hz pulse repetition rate. The large mean-to-sigma ratios found at those frequencies are due to the $\sin(x)/x$ character of the spectrum of the envelope. For instance, at the envelope frequency of 50 Hz, the mean-to-sigma ratio is about 23. This may indicate that the period itself has a special meaning for the type of analysis we performed. An optimum detection scheme would be likely to focus on the regions where the mean-to-sigma ratio is high, i.e., the harmonics of the period, which in turn would then be vulnerable to an increased variability due to jitter in those regions. The average mean-to-sigma ratio of all spectral components save for those associated with the pulse repetition rate is 2.03, in accordance with the above theoretical consideration.

[1]Similarly high threshold values were obtained by the first author for the two-pulse stimuli, when our experiments were repeated in a practical course with untrained students as subjects.

[2]In contrast to what one might conclude from a visual inspection, the slopes of the two data sets are also different if only gap durations of 10 ms or more are considered. For this subset of the data, the linear-regression fit yields a slope of 0.21 for the two-pulse data and of 0.13 for the 21-pulse data. These values differ statistically on a 2% level of significance.

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