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Human event-related brain potentials to auditory periodic noise stimuli

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Abstract

Periodic noise is perceived as different from ordinary non-repeating noise due to the involvement of echoic memory. Since this stimulus does not contain simple physical cues (such as onsets or spectral shape) that might obscure sensory memory interpretations, it is a valuable tool to study sensory memory functions. We demonstrated for the first time that the processing of periodic noise can be tapped by event-related brain potentials (ERPs). Human subjects received repeating segments of noise embedded in non-repeating noise. They were instructed to detect the periodicity inherent to the stimulation. We observed a central negativity time-locked on the periodic segment that correlated to the subjects behavioral performance in periodicity detection. It is argued that the ERP result indicates an enhancement of sensory-specific processing. © 1998 Elsevier Science Ireland Ltd.

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Periodic noise as an auditory stimulus was introduced to psychophysics in order to investigate the lower limit of auditory periodicity analysis [4]. There, subjects were presented with periodically recurring iterations of a segment of white noise that were seamlessly connected to each other. For cycle lengths of two seconds or more this sounded perfectly like homogenous non-repeating white noise. For cycle lengths of one second or less subjects did easily remark the periodic nature of the stimulus due to the perception of recurring faint events such as clanks and beeps; (demonstrations of periodic noise stimuli can be found at http://www.uni-leipzig.de/~psycho/kaernbach/pn/).

Whereas this stimulus was originally designed to study periodicity detection, it is of indubitable value to the study of sensory auditory memory (echoic memory) [3]. It has served in numerous psychophysical studies, testing the intra- and inter-subject stability of the perceived faint events [6], studying their temporal and spectral extent [7], varying the spectral shape of the carrier [12], or estimating phase sensitivity [16] or time-constants [2,8] of echoic memory. To our knowledge, however, it has not yet been investigated whether the processing of periodic noise stimuli can be probed by event-related potentials (ERPs).

In one approach, auditory sensory memory has been studied measuring event-related magnetic fields elicited by repeating sinusoidal tones at varying repetition rates [9]. However, this approach is based on a hypothetical relation between auditory trace strength and the amplitude of the magnetic components. Moreover, it is unclear to what extent the measured effect could be due to adaptation instead of memory. Other studies measured late cognitive change-specific potentials elicited by infrequent changes of repeating tonal patterns [1,10,11,15,17]. This approach clearly studies memory as the measured ERP components result from a comparison of the stimulus with a detailed representation of the standard stimulus (e.g. of time order in [17]). However, all these studies used simple sinusoidal tones or tonal patterns consisting of sinusoidal tones that may have been memorized using a symbolic rather than a sensory representation. This would be different with a periodic noise stimulus as the latter does not contain simple

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physical cues such as onsets, offsets, gaps, or spectral peaks giving rise to well-defined percepts such as stimulus begin, stimulus termination, silent interval, or pitch.

The present study aims at determining the ERPs elicited by periodic noise. Using a cyclical stimulus such as periodic noise in an ERP study has the obvious disadvantage that the components cannot be labeled with respect to the onset of the stimulus as any point in the cycle might have served as starting point to the subject. To avoid this problem, we used semi-periodic noise [7], in which a certain 100-ms segment recurs every second, the remaining 900 ms being filled with non-repeating noise of the same amplitude. The relevant part of the stimulus is restricted to 100 ms, which makes it possible to identify ERP components with respect to stimulus onset. This stimulus has the additional advantage that it is not easy to detect the repeating segment. If not listening carefully, it sounds just like white noise. The performance of the subjects in detecting the periodicity will hence vary so that the ERP data can be compared with behavioral data. For details of the noise generation [6,7]. In order to make the task not too difficult we used good detectable segments ([2.0,2.1] and [5.3,5.4] of the noise sample of experiment 2 in [7]). The noise was converted at a sampling rate of 20 kHz. It was presented at 60 dB hearing level (HL) on Sennheiser HD 435 headphones.

In order to help the subjects to find the repeating segment, the rhythm of the periodic noise was indicated by two flashing light-emitting diodes (LEDs) positioned around another pair of steady LEDs that served as fixation point. The flashing LEDs were on exactly for the same time that the recurring segment was presented (100 ms). To further help the subjects, the periodic noise started with a fast and easy-to-detect rhythm of 5 Hz (200 ms, i.e. only 100 ms non-repeating noise between the segments). The non-repeating portion was then lengthened during 25 s until the final rhythm of 1 Hz was reached. When this was the case, it was indicated to the subjects by additional LEDs flashing once.

All subjects performed at least two training sessions, each lasting around 60 min. In the recording session, the flashing LEDs did flash 20 more times after the final rhythm had been reached, at most occasions accompanied by the recurring segment. Sometimes, however, the LEDs did flash but the 100-ms segment did not recur. Another 100-ms piece of random noise had taken its place. Perceptually, this corresponds to an omission, as no specific perceptual event will be elicited by random segments. Omissions occurred with a probability of 1:4. Each omission was followed by at least two intact presentations before the next omission could occur. The actual omission rate was hence 1:6, and a maximum number of six omissions could occur during a block of 20 task-relevant presentations. Omissions were included to determine the subjects ability to detect the recurring segment as subjects were instructed to count these omissions. After each block they entered their count. Feedback was given, indicating the real number of omissions. The average duration of a block was about one minute including the answering interval. The subject performed 40 blocks of 20 presentations, giving in total 800 presentations. About a sixth of this (130 presentations) were omissions. Presentations following directly after an omission (130 presentations approx.) were not counted as standard as they did not represent a repetition at the stated rate (1 s). There were hence about 530 standard stimuli in the recording session.

Twenty students participating in an optional second-year EEG course served as subjects. Subjects gave informed consent after the nature of the study was explained to them. All subjects reported normal hearing. Subjects were seated in a comfortable chair in an electrically attenuated room. They were shielded from environmental noise by the stimulus itself which was white noise at 60 dB HL. Three subjects served in pilot experiments testing the equipment and the software, and one further subject aborted the experiment. Any data presented in this paper refer to the remaining 16 subjects (seven male).

EEG was measured with tin electrodes for 19 scalp locations of the 10–20 system: FP1, FP2, F7, F3, FZ, F4, F8, T3, C3, CZ, C4, T3, T5, P3, PZ, P4, T6, O1, and O2. The horizontal and vertical EOG was monitored with bipolar pairs of electrodes from the outer canthus of the left eye to the outer canthus of the right eye and from above and below the right eye, respectively. The reference electrode was placed at the nose. EEG and EOG were digitized at 200 Hz (bandpass 0.1–40 Hz) in continuous mode. Epochs were calculated off-line and were of 1000 ms duration (including a 100 ms prestimulus baseline). Epochs with values exceeding ±50 μV in the EOG were rejected from further analysis. This occurred in less than 15% of all epochs. ERPs were averaged separately from standard stimuli and omissions.

Behavioral performance was determined calculating the correlation coefficient r of the number n_s entered by the subject and the real number n_r of omissions in a specific block. The higher r the better the subject was able to deal with the task. In order to estimate the signal-detection criterion employed by the subject, the ratio n_s/n_r of the real and the entered count was determined. These two parameters permitted an indirect estimation of the two signal-detection parameters of the subject. For convenience, these will be expressed as hit rate and false alarm rate for the omissions instead of for the recurring segment.

The average correlation was 0.24, and the average ratio n_s/n_r was 0.9, i.e. the subjects counted on average 10% less omissions than were present. We applied a monte-carlo technique simulating 10 000 sweeps of 60 blocks of 20 trials, with the same rule for the omissions as in the experiment. We found that a hit rate of 54% and a false alarm rate of 14% would lead to the observed average correlation and n_s/n_r ratio. This is equivalent to a two-alternatives forced-choice (2AFC) performance of 70%. The best subjects produced correlation coefficients that correspond to a 2AFC performance around 90%, whereas the worst subjects produced correlation coefficients that are well compatible with chance performance. For the following analysis, subjects

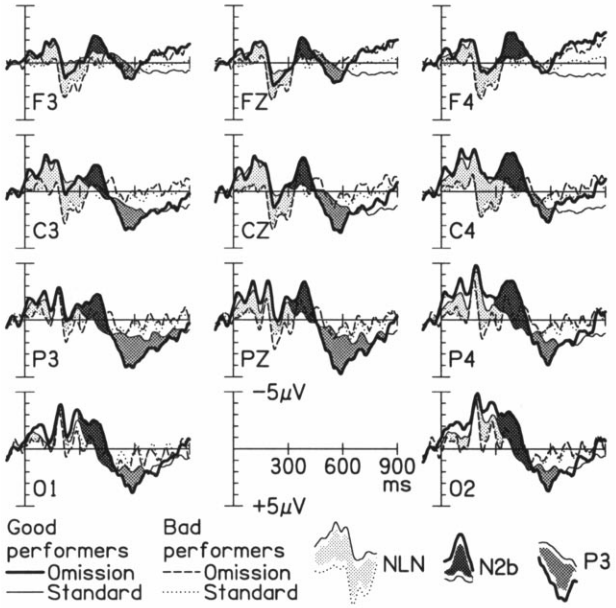

Fig. 1. ERPs elicited by standard stimuli (i.e. the recurring noise segment) and omissions (i.e. a random noise segment in place of the recurring segment). Averaged over subjects with good (r>0.2) and bad ($r < 0.1$) performance. Waves are plotted in the interval from –100 to 900 ms relative to the onset of the recurring segment.

were classified into good performers ($r > 0.2$, seven subjects), bad performers ($r < 0.1$, five subjects) and medium performers (four subjects, not analyzed).

Fig. 1 shows the ERPs elicited by standard stimuli (i.e. segment was present) and the omissions, averaged separately for good and bad performers. The two curves for the bad performers (dashed and dotted lines) nearly coincide, i.e. it makes no difference to the ERP whether the segment was present or not. The only structure to be seen in these curves is due to visual potentials elicited by the LEDs. In particular, there is no significant deviation from zero before 190 ms.

The curves for good performers (solid lines) show for both types of stimulus a marked negativity during the first 200 to 300 ms that is not to be found with the bad performers. This negativity (we call it henceforth noise-locked negativity (NLN), shaded in light gray in Fig. 1) is largest over C3/CZ/C4. Fig. 2 shows the difference between good and bad performers for standard stimuli. The NLN peaks at 200 ms. For the following analysis of variance (ANOVA), NLN was measured as the mean of the 180–220 ms interval relative to the onset of the noise segment. The ANOVA including the between-subjects factor performance (levels: good vs. bad), and the within-subjects factors stimulus type (levels: standard vs. omission) and lead (levels: C3, CZ, C4) yielded a main effect of performance ($F(1,10) = 12.61$, $P < 0.005$) indicating enhanced negativity in NLN with good as compared with bad performers. Thus NLN is correlated with periodicity detection. It should be noted that due to the unstructured nature of the stimulus the recurring segment cannot be detected on the basis of simple features such as amplitude onsets or frequency characteristics: inspection of the spectrogram does not reveal the physical basis of the perceived features [7]. It can hence be assumed that the NLN corresponds to a sensory rather than to a symbolic processing.

The good performers show clear effects of the presence or non-presence of the segment. In the case of an omission there is an additional negativity at about 395 ms (shaded in dark gray in Fig. 1) and a positivity, largest at about 590 ms (shaded in medium gray). For the following ANOVA, this N-P-complex was computed as the difference between the individual mean amplitudes of the positivity (interval 570–610 ms) and the negativity (interval 375–415 ms). The ANOVA yielded main effects of performance ($F(1,10) = 5.43$, $P < 0.042$) and stimulus type ($F(1,10) = 9.38$, $P < 0.012$), and a performance × stimulus type interaction ($F(1,10) = 7.01$, $P < 0.024$). These effects are due to large N-P complex elicited by omissions in good performers. This N-P complex represent the well-known N2b and P3 components, commonly being elicited by deviant events in repetitive stimulation in attentive listening tasks [14]. Its presence for good performers only is a post-hoc justification of the behavioral classification of the subjects.

To our knowledge, the NLN and the N-P complex are the first ERPs that were ever recorded with periodic noise. Whereas the nature of the N-P complex is evident, the NLN observed for good performers deserves some discussion. If we consider the NLN as a sign of the activity of the echoic memory, we can exclude that it corresponds to a late modality-unspecific cognitive potential since it is too early. Please note that the sound segment extends to 100 ms and the NLN peaks at 200 ms. The NLN could, however, represent the top-down controlled activation of sensory areas just

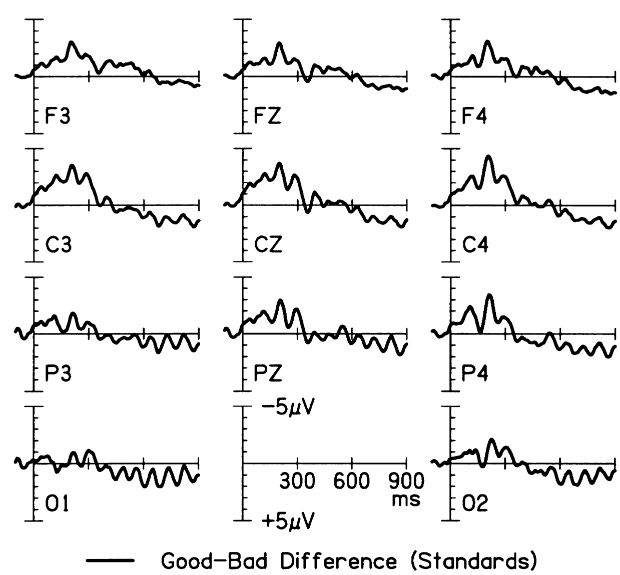

Fig. 2. Difference wave between good and bad performers' ERPs to the recurring segment (standard stimulus). Waves are plotted in the interval from –100 to 900 ms relative to the onset of the recurring segment.

in time to enhance auditory signal processing. In this case it could be regarded as a kind of sensory-specific contingent negative variation [5]. The subjects know the moment in time when to do so due to the visually cued constant rhythm of the stimulus. This top-down processing would depend on the previous detection of the noise segment by echoic memory. It can hence be speculated that this activity is due to a top-down tuning of auditory feature detectors. It seems likely that these feature detectors deal with complex features and not with simple onsets, offset, energy peaks and the like. Bad performers have missed the segment and their echoic memory just does not know what to tell the sensory areas to listen at, and, as a consequence, no sensory processing time-locked on the recurring segment can be activated. In contrast, good performers activate their sensory areas for both types of stimuli in order to better judge the presence of the noise segment. This interpretation is in accordance with a recent study demonstrating activation of auditory cortex by omission of auditory stimuli [13].

In summary, the present study showed that a difficult task involving retention of a sensory coded noise segment in echoic memory can only be solved by those subjects that show an early negativity locked on the relevant part of the stimulus. This result may be seen as an indication that echoic memory acts on sensory stages to produce the percepts audible in periodic noise. The study demonstrates that periodic noise stimuli may elicit ERPs although the recurring segments cannot be distinguished from non-repeating noise on the basis of simple physical cues (such as onsets, energy peaks or spectral shape). Thus it must be memorization of complex auditory features that underlie the present ERP effects of periodicity detection.

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