

Logarithmic laws of echoic memory and auditory change detection in humans

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Running title: Logarithmic law of echoic memory

Abstract

The cortical mechanisms underlying echoic memory and change detection were investigated using an auditory change-related component (N100c) of event-related brain potentials. N100c was elicited by paired sound stimuli, a standard followed by a deviant, while subjects watched a silent movie. The amplitude of N100c elicited by a fixed sound pressure deviance (70 dB vs. 75 dB) was negatively correlated with the logarithm of the interval between the standard sound and deviant sound (1 ~ 1000 ms), while positively correlated with the logarithm of the duration of the standard sound (25 ~ 1000 ms), indicating that the temporal representation of echoic memory is logarithmic. The amplitude of N100c elicited by a deviance in sound pressure, sound frequency and sound location was correlated with the logarithm of the magnitude of physical differences between the standard and deviant sounds, suggesting that Weber-Fechner's law holds for the automatic cortical response to sound changes within a suprathreshold range.

The quick detection of an abrupt change in the environment is one of the most important functions of sensory systems. Actually, neural networks sensitive to sensory changes are known in humans^{1, 2}. Such a change-detecting system should orient animals to a new event involuntarily and facilitate subsequent behavior. Therefore, knowing the involuntary process of activation in the brain in response to sensory changes should help us to understand the mechanisms of the sensory change-detecting system.

To respond to any kind of sensory change, a new event must be compared with a preceding condition, that is, the change-detecting process should involve short-term sensory memory. Therefore, brain activity in response to sensory changes is expected to be affected by the strength of memory for a preceding event (memory storage), time between the new event and the preceding event (memory decay), and the degree of physical difference between the two events. The behavior of brain activity as a function of these parameters has not been studied in detail. In this study, we recorded a change-specific cortical activation in the auditory system using electroencephalograms while subjects watched a silent movie. Results supported the hypothesis and we found some laws relating to the change-detecting system and echoic memory.

RESULTS

To create an abruptly changing sound stimulus without distorting the sound waveform at the transition is difficult. In the present study, we used a train of brief tone pulses³ (Fig. 1a). The pulse was an 800-Hz pure tone of 25-ms duration including 5-ms rise and fall times. When a given number of the brief tones were arranged without a

space, a standard sound of a given length could be made. By inserting a similar but physically different tone pulse at a desired place, a deviant sound with an abrupt change at a given time could be obtained without any undesired edge. Figure 1b shows an example of brain potentials evoked by a standard sound of 500 ms (20 pulses) at 70 dB SPL, and a deviant sound consisting of a 250-ms standard sound at 70 dB followed by a 250-ms deviant sound at 75 dB. We refer to the train of brief standard tone pulses as the Control stimulus and the train of control tone pulses followed by deviant tone pulses as the Deviant stimulus. A clear negativity peaking at around 100 ms following the change was recorded at Fz referenced to the nose. We refer to this component as N100c (change-related N100 component). N100c is accompanied by a positive counterpart at mastoids (P9 and P10), suggesting symmetric dipoles in the auditory cortex in both hemispheres (Supplementary Fig. 1). Therefore, we used a derivation of Fz referenced to linked mastoids, which improved the S/N ratio of the potentials. Since some electric activity was present at a latency of interest in the waveform following the Control stimulus without a change, we presented the Control and Deviant stimuli at an even probability in all the experiments, and obtained a difference waveform by subtracting the waveform for the Control stimulus from that for the Deviant stimulus. The difference waveform could therefore, be attributed to the occurrence of the change. The latency and amplitude of N100c in the difference waveform of each subject were used for the analysis.

Figure 1c shows little effect of attention on N100c. All experiments were carried out while subjects watched a silent movie. Under the conditions, N100c was elicited stably

with a long time course (Fig. 1d). Figure 1e shows effects of an abrupt change on N100c. When a 70dB sound and a 75dB sound were presented at an even probability, N100c could not be elicited at all ($1e-2$). This indicates that N100c is due not to the louder sound itself but to the abrupt change in sound pressure. Therefore, an automatic memory-comparison process appears necessary to shape the N100c component. In the following two experiments, we tested this using a 70dB sound for the standard and 75dB sound for the deviant.

Experiment 1

If N100c depends on the comparison of the present sound with a preceding standard, and thus depends on echoic memory, cortical activation due to the change should be affected by the interval between the standard and deviant sounds. In Experiment 1, effects of the interval were examined by varying it from 1 to 1000 ms while the duration of the standard sound (500 ms) and inter-trial interval (offset-to-onset, 300 ms) were kept constant. Results show that the amplitude of N100c decreased with an increase of the interval (Fig. 2a). The N100c amplitude was negatively correlated with the logarithm of the interval. The correlation coefficient, r^2 , was $0.84 \sim 0.99$ (0.94 ± 0.06). The peak latency of N100c increased with an increase in the interval with a logarithmic function. Therefore, the amplitude and latency were negatively correlated (latency = $-4.7 \times \text{amplitude} + 125$, $r^2 = 0.97$, mean data). For this and subsequent experiments, waveforms of all the subjects are shown in Supplementary Figs. 2~4. The mean peak latency and peak amplitude of N100c are listed in Supplementary Table 1.

Experiment 2

Next, we examined effects of the duration of the standard sound. Results described above led us to expect that a longer standard sound, and thus stronger memory for the standard, would result in a larger N100c. We tested four durations of the standard sound, 25, 100, 500 and 1000 ms, while keeping the interval between the standard and deviant sounds (0 ms), and inter-trial interval (300 ms) constant. Results were as expected (Fig. 2b). The amplitude of N100c as a function of the duration of the standard sound was logarithmic ($r^2 = 0.9 \sim 0.99$, 0.96 ± 0.04). The latency of N100c was negatively correlated with the amplitude (latency = $-2.6 \times \text{amplitude} + 120$, $r^2 = 0.91$).

Experiment 3

The above results indicated the temporal aspect of both the storage and decay of echoic memory to be logarithmic. Given that several features of a sound can be stored in echoic memory⁴ and the generation of N100c depends on a memory-comparison between the new event and preceding state, the degree of the physical difference between the standard and deviant sounds should affect the amplitude of N100c. We next tested this using three variables, sound pressure, sound frequency and sound location, with a fixed standard-deviant interval and a standard of a fixed duration. In all the three experiments, the Control stimulus was a 500-ms 800Hz standard sound at 70 dB. The Deviant stimulus was a 250-ms standard sound followed without a blank by a 250-ms deviant sound. The inter-trial interval was 250 ms. The deviant was 72, 73, 74, 75 or 76

dB for the sound pressure experiment, and 808, 816, 824, 840 or 880 Hz for the sound frequency experiment. The deviant sound for the sound location experiment was created by inserting a silent period of 0.1, 0.2, 0.3, 0.4 or 0.5 ms into the sound of one ear, that is, an interaural time delay (ITD) of 0.1~ 0.5 ms. Results are shown in Fig. 2c. For all three variables tested, the amplitude of N100c was linearly correlated with the logarithm of the magnitude of physical differences between the control and deviant sounds ($r^2 = 0.95 \pm 0.03$ for sound pressure, 0.94 ± 0.04 for sound frequency and 0.91 ± 0.1 for sound location). The latency of N100c was negatively correlated with the logarithm of the magnitude of the difference ($r^2 = 0.78 \pm 0.22$ for sound pressure, 0.85 ± 0.05 for sound frequency and 0.6 ± 0.17 for sound location). When the latency of N100c was plotted against amplitude, there was a negative linear correlation for the sound pressure and sound frequency changes (Fig. 2d). Both fitting curves showed a similar slope, suggesting that the latency depends on the amplitude. This notion is further supported by the fact that a similar relationship between the latency and amplitude of N100c was also found for Experiment 1 ($r^2 = 0.97$ on average data) and Experiment 2 ($r^2 = 0.91$) where the magnitude of the change (70 dB vs. 75 dB) was fixed (Fig. 2d). On the other hand, effects of the magnitude of the frequency change on the latency were evident, and the relationship between latency and amplitude was logarithmic (or power function), suggesting an additional delay of N100c specific to the detection of a change in sound frequency, probably at an earlier stage than the common N100c-generating system. The difference in the y intercept of the regression line between sound pressure and sound location suggests that a change in the location of a sound takes about 10-ms longer to

detect than a change in sound pressure.

DISCUSSION

The present results suggested that N100c is a product of an automatic change-detecting system, which receives auditory information processed in earlier cortical areas and generates change-specific signals proportional to the magnitude of the deviance. It is worth noting that in our previous study, it took about 8 ms for signals in the primary auditory cortex to reach the posterior parietal cortex⁵ where spatial sound information is transformed from head-centered to body-centered coordinates⁶. Therefore, the delay of N100c for the sound location deviance in this study might indicate the time delay necessary to process at the parietal lobe. Given that sound information reaches the primary auditory cortex as early as 17 ms after the onset of a sound stimulus and the time delay between two sequential cortical activations is about 4 ms⁵, the latency of N100c is late enough to consider that it belongs to a very high level of processing or else is due to a feedback or lateral pathway. Our previous magnetoencephalographic studies suggest that the activation profile of N100c is likely due to a processing pathway other than feedforward projection⁷. Therefore, it seems possible that the N100c-generating system receives integrated information as a difference between the two recent events from a memory-specific cortical region. In this case, any kind of auditory change activates the same group of neurons.

Results of Experiment 3 showed that Weber-Fechner's law holds for the automatic cortical response to auditory changes within a suprathreshold range. Although

measuring the magnitude of a perceived difference in individuals would be difficult like measuring the magnitude of perceived intensity, the present results suggest that the magnitude of the perceived difference would be logarithmically related to the degree of the difference between the two stimuli. In terms of the survival of animals, such a system would work well within a physiologically significant range of sensory changes. In this regard, a limitation of Weber's law, that just noticeable differences are constant only within a certain range of sensory intensities, seems reasonable. When the stimulus or the difference between a new event and the previous one is strong enough to fully orient animals to the new event, no further increase in brain activity specific to change detection seems necessary.

The results of Experiment 1 that a decay of echoic memory has a logarithmic function in time, are consistent with psychological studies using a dichotic listening task showing that recall performance decreases with time in a typical negatively accelerated fashion^{8, 9}. In addition to this, the present study showed that echoic memory has a logarithmic storage function in time. Although whether this rule can be applied to other more complicated memory systems is unclear, these results might show one fundamental mechanism of memory. Echoic memory shares features with short-term memory or working memory¹⁰. Since the present results show that the behavior of echoic memory can be understood through N100c, N100c would be a useful tool to investigate memory systems in addition to psychological methods.

Although the present study did not employ a specific stimulation paradigm, N100c appears homologous to a so-called mismatch negativity (MMN), which can be elicited

under an oddball paradigm using frequently occurring standards and infrequently occurring deviants. MMN is a change-specific component of event-related brain potentials elicited by any discriminable change in auditory stimulation. MMN is thought to be the outcome of a discrimination process where the deviant event is found to be incongruent with the memory representation of the preceding stimuli^{11, 12}. It is suggested that MMN could be used to determine the degree of abnormality in auditory perception, attention and memory, and in fact, previous studies found attenuated or delayed MMN in various clinical disorders such as schizophrenia. We believe that the stimulation paradigm used in this study will improve the method for replicable recordings of the change-related response in individual patients, and in addition, for separate evaluations of discrimination accuracy, memory establishment and memory decay. For example, a patient with Alzheimer's disease might have normal discrimination acuity (Experiment 3) but a faster decay of memory (Experiment 1) than normal subjects¹³. An example of a paradigm to examine discrimination accuracy (sound frequency, pressure and location) within a very short time is shown in Supplementary Fig. 5.

METHODS

The experiment was performed on seven (one female and six males) healthy right-handed volunteers, aged 26-45 years (31 ± 7). The study was approved in advance by the Ethics Committee of the National Institute for Physiological Sciences, Okazaki,

Japan, and written consent was obtained from all the subjects.

Stimulus

To evoke a change-related cortical response, we used a train of brief tones (Fig. 1a). The brief tone (standard) was 800 Hz in frequency and 25 ms in length (5 ms rise/fall). By use of a train of brief standard tones followed by physically deferent tones, we could easily create an abruptly changing tone stimulus without any undesired edge. In this paper, we refer to the train of standard tones as the Control stimulus and the train containing physically different tones (deviant) as the Deviant stimulus. For example in Experiment 3 for the detection of the change in sound frequency, the Control stimulus was a train of 20 brief tones (500 ms in total duration) 800 Hz in frequency, while the Deviant stimulus was a train of ten tones of 800 Hz followed by ten tones of a different frequency.

Recordings

Evoked potentials were recorded in five experiments for all of the seven subjects. An exploring electrode was placed at Fz referred to the linked mastoids (P9-P10) of the 10-10 system. We used a Fz-linked P9 and P10 derivation, since the main component at around 100 ms following a change occurrence (N100c) shows a maximum amplitude at Fz (negativity), and a positive counterpart at P9 and P10. A pair of electrodes placed on the supra- and infra-orbit of the right eye was used for recording the electro-oculogram (EOG). The impedance for all the electrodes was under 5 k Ω . The responses were recorded with a 0.5-100 Hz bandpass filter at a sampling rate of 1000 Hz. The period of analysis was from at least 100 ms before to 350 ms after the onset of deviant sounds. In

each experiment, 200 trials without artifacts were averaged for both the Control and Deviant stimuli. After obtaining each waveform, a difference waveform was calculated by subtracting the waveform for the Control stimulus from that for the Deviant stimulus. Then the difference waveform was digitally filtered with a high-cut filter of 30 Hz for subsequent analyses. Since we used a train of 25-ms tones, sharp activities at 40 Hz (stimulus-locked activity probably in the primary auditory cortex) were sometimes problematic for precise determination of the response latency and amplitude when we did not use an appropriate high-cut filter.

Procedures

The experiments were conducted in a quiet, electrically shielded room. The subjects sat in a chair and watched a silent movie on a screen 1.5 m in front of them throughout the experiments. Sound stimuli were presented binaurally through headphones at 70 dB SPL. Five experiments were carried out on each subject on different days.

Experiment 1

First, effects of the interval between the Control and Deviant stimuli on N100c were examined. The Deviant stimulus was a 500-ms 800Hz pure tone at 70 dB (control sound) followed by a deviant sound of 100 ms at 75 dB. The interval between the control and deviant sounds was either 1, 10, 100 or 1000 ms. The Control stimulus was identical to the Deviant stimulus except that a 70dB sound was used instead of the deviant 75dB sound. The two stimuli were presented in separate blocks at the same probability but randomly with an inter-trial interval (offset-to-onset) of 300 ms. The order of the four sessions (four different intervals) was randomized among subjects.

Original waveforms of all the subjects are shown in Supplementary Fig. 1b. Since the grand-averaged high-cut (30 Hz) waveforms across subjects are shown in Fig. 2, original difference waveforms (non-filtered) are shown in Supplementary Figs 1 ~ 3.

Experiment 2

Second, effects of the duration of the control sound were examined. The Deviant stimulus consisted of two sounds. The first sound (control) was an 800Hz pure tone at 70 dB with a duration of 25, 100, 500 or 1000 ms, and the second sound was a 100-ms 800Hz pure tone at 75 dB. There was no blank between the two sounds. The Control stimulus was similar to the Deviant stimulus but with a 70dB sound for the second sound. The two stimuli were presented at an even probability but randomly with an inter-trial interval of 300 ms. The order of the four sessions (four different durations) was randomized among subjects.

Experiment 3

Third, effects of the magnitude of the physical difference between the control and deviant sounds were examined for sound frequency, sound pressure and sound location. In all three experiments, the Deviant stimulus was a 250-ms 800Hz pure tone at 70 dB (control sound) followed without a blank by a 250-ms deviant sound. The Control stimulus was a 500-ms 800Hz sound at 70 dB. For the experiment on frequency change, the deviant sound was 808, 816, 824, 840 or 880 Hz. The deviant sound for the experiment on sound pressure change was 72, 73, 74, 75 or 76 dB. The deviant sound for the experiment on sound location change was created by inserting a blank of 0.1, 0.2, 0.3, 0.4 or 0.5 ms into the sound for one ear, that is, an interaural time delay (ITD) of

0.1 ~ 0.5 ms. All the subjects reported that the sound abruptly moved to the left (or right) on hearing the Deviant stimulus with an ITD of 0.5 ms. The blank was inserted into the left sound for three subjects and into the right sound for four. To confirm that the effect of the ITD on N100c is actually due to the phase shift between both ears, we additionally tested an insertion of 1.25 ms silence into the left sound (insertion of a longer silent period but without an ITD) in three subjects. However, this deviant sound did not evoke N100c at all in two subjects and evoked a small N100c at a longer latency (215 ms) than those for the other five ITD sounds (100 ~ 130 ms) in one subject, which was probably due to gap detection.

The two stimuli (Control and Deviant) were presented in separate blocks at an even probability randomly with an inter-trial interval of 300 ms. The order of the five sessions (five different Deviant stimuli) was randomized among subjects.

Analysis

In all the experiments, the amplitude of N100c was measured and compared among conditions. The amplitude of N100c was determined as a peak-to-peak amplitude between the peak of N100c and a positive peak about 50 ms earlier (probably corresponds to the so-called P50). This procedure minimizes problems due to a baseline shift. Although we considered that the amplitude and latency of P50, N100 and P150 evoked by sound changes basically behave similarly under the experimental conditions in the present study, P50 was too small for a precise amplitude measurement and P150 tended to jitter more than N100 in latency. Therefore, we used N100 in this study.

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Figure Legends

Fig.1. Change-specific N100c component of event-related potentials. a, the sound stimulus with an abrupt change used in this study. b, brain potentials recorded at Fz and mastoids produced by the Control stimulus with a 500-ms standard sound (800 Hz, 70 dB SPL) and Deviant stimulus with a 250-ms standard followed by a 250-ms deviant (75 dB). c, effects of attention on N100c. A similar N100c was elicited when the subject ignored the sound (blue) and attended (pink) the sound. d, four consecutive recordings of 200 trials when the subject watched a movie and ignored the stimulus. F, effects of the abrupt change on N100c. When a 500-ms sound at 70 dB and a 500-ms sound at 75 dB were presented at an even probability (2), N100c was not elicited, which clearly contrasts with the upper trace (1) when the abruptly changing deviant was used. Arrowheads indicate the change onset.

Fig. 2. Grand-averaged waveforms of N100c across seven subjects and the peak amplitude and latency of N100c. a, effects of the interval between the standard and deviant sounds. Four intervals, 1, 10, 100, and 1000 ms, were tested. b, effects of the duration of the standard sound. Four durations, 25, 100, 500 and 1000 ms, were tested. c, effects of the magnitude of deviation on N100c. Sound pressure (70 dB vs. 72, 73, 74, 75 and 76 dB), sound frequency (800 Hz vs. 808, 816, 824, 840 and 880 Hz) and sound location (interaural time delay, ITD, of 0.1, 0.2, 0.3, 0.4 and 0.5 ms) deviations were tested. The mean amplitude and latency across subjects of each experiment are plotted against the degree of the deviation of each variable. Error bars indicate \pm SE. The

correlation coefficient, r^2 , in this figure show values calculated using the mean data. d, the mean peak latency of N100c as a function of its amplitude in each experiment. The right graph compares the latency-amplitude relationship among Experiments 1, 2 and 3 (sound pressure deviation).



