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Median method for eliminating infrequent artifacts and identifying the signals blurred by latency jitter and uncertain occurrence

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Most researchers have employed the average method in the identification of event-related brain potentials (ERPs) because they have assumed that the averaging process results in the cancellation of any type of noise. However, the average method is less effective than is the median method for unexpected, infrequent artifacts. Furthermore (and significantly), the average method does not work well for detecting the endogenous, psychological signals that are noninvariant across every trial. Ruchkin (1988) described two types of possible signal variation in amplitude and in latency. The median method is effective for extreme cases of these variations (i.e., the lack of some signals), even if the amount of data is small and their distribution is non-Gaussian. Importantly, in the latter situation, the trial-to-trial latency jitter of the signal is very difficult to eliminate, which introduces obscure errors into the average ERP measurements. We found that the waveform that was generated by the median method was less affected by this jittering than was that generated by the average method. This effect was demonstrated by simulating the signals of artificial and actual ERP data, when the distribution of latency variation was Gaussian.

The study of event-related brain potentials (ERPs) has made great progress since the average method (Dawson, 1954) was generally adopted for psychological experiments using electroencephalography (EEG) in laboratories throughout the world. The computational procedure of the average method is very simple, requiring only a small amount of random access memory in a microcomputer. The average procedure results in an increase of the signal/noise ratio in proportion to the square root of the number of trials, if the signal is invariant and the noise is stationary across every trial (Perry, 1966). However, in attempting to detect the endogenous signals related to psychological processes, the application of the average method creates several problems. One of these is the occasional occurrence of extracerebral potentials when calculating the ERP. The most abundant source of extracerebral potentials is the human body itself. Skeletal muscle activity, eye blinking, and eye movement can occasionally cause changes in potential on the scalp. Averaged ERPs tend to be contaminated by such infrequent artifacts (Yabe, Saito, & Fukushima, 1993). Furthermore, the use of a small number of trials—as is usually the case when measuring endogenous ERPs—enhances this tendency. Most experimenters are cautious about including trials contaminated by infrequent artifacts. For example, they record the electrooculogram (EOG) on a separate channel and then reject those trials in which the EOG change exceeds a criterion amplitude. However, it is unlikely that any set of artifact channels will detect all of the sources of artifacts.

Another problem lies in the variation of brain signals themselves. Endogenous signals reflect psychological processes that may be variant in each trial. As Picton and Hillyard (1988) have proposed, the subject might ignore the sequence of stimuli and attend to something else while he or she is counting the oddball stimuli. Without a motor response, the experimenter cannot know whether the subject has neglected his or her task in each trial. Furthermore, ERP amplitude might be influenced by the subject's confidence in signal detection, as Squires, Hillyard, and Lindsay (1973) have suggested. Therefore, the assumption that the same psychological process occurs constantly in every trial is tenuous. Thus, the psychological signal should vary in each trial. Ruchkin (1988) described two types of possible signal variation in amplitude and in latency. Importantly, in the latter, the trial-to-trial latency jitter of the signal is very difficult to eliminate when using the average method, because this approach introduces obscure error into the average ERP measurements. Many studies that measure single-trial ERPs have also reported the phenomenon of latency jitter (Kerkhof & Uhlenbroek, 1981; Michalewski, Prasher, & Starr, 1986; Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984a, 1984b).

The purpose of the present study was to examine whether the median method (Borda & Frost, 1968; Yabe

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et al., 1993) can address the above problems—particularly the trial-to-trial latency jitter of the signal—that are encountered in the application of the average method. The median wave consists of the median values at a series of time points. Each value is the middle measurement in an ordered set of amplitudes at the same time point. The median method described here is different from that of Borda and Frost. Every trial needs to be corrected in terms of the baseline before estimating the median value as a representative of distribution on every time point (a brief description can be found in the Appendix).

Effect on Data From a Small Number of Trials

The averaged value is an appropriate measure of any central tendency, if the measurements have a Gaussian distribution. However, endogenous ERPs are often measured by paradigms yielding a small number of trials, because a larger number may lead to habituation (Picton, Hillyard, & Galambos, 1976) and other problems. Given such a small amount of data, the averaged value at each time point may not be an appropriate measure of the central tendency. Because the median value is an accepted measure of the central tendency of a group of values, even when their distribution is non-Gaussian, the median method is valid even when applied to a small number of trials.

Effect on Infrequent Artifacts

Extracerebral potentials—such as those arising from eye movements and muscle activity—produce erroneous changes in potential on the scalp. Because these potentials distort the resulting ERP, trials that include them should be excluded. Most experimenters take precautions against including trials contaminated by such artifacts in the computation of the ERP. It is, however, implausible to prepare a sufficient number of channels to detect all artifacts. Alternatively, experimenters may increase the number of delivered stimuli, in order to compensate for the artifact rejection. As a result, the number of trials may be sufficient, even after the screening procedure. Such a large number of trials may, however, lead to habituation (Picton et al., 1976) and to variation in the psychological conditions caused by fatigue.

When infrequent artifacts are present in the data set, the waveform that is generated by the median method is less affected by the artifact than is that generated by the average method. Figure 1 illustrates this effect on the infrequent artifact of eye blink. Both the median method and the average method were applied to actual data. While 1 normal subject performed a reaction time task without suppressing eye movement or blinking, ERPs such as contingent negative variation (CNV; Walter, Cooper, Aldridge, McCallum, & Winter, 1964) were recorded from the Fz, Cz, and Pz leads. The EOG was also recorded from above and below the outer canthus of the right eye. In this case, the criterion value of rejection was deliberately set at a high value to include unrejected EOGs in the data. Consequently, in contrast with the median waves, the average waves in Fz and Cz were extremely distorted by unrejected EOG activity. Thus, the increased positivity and the decreased negativity on the average waves were erroneous.

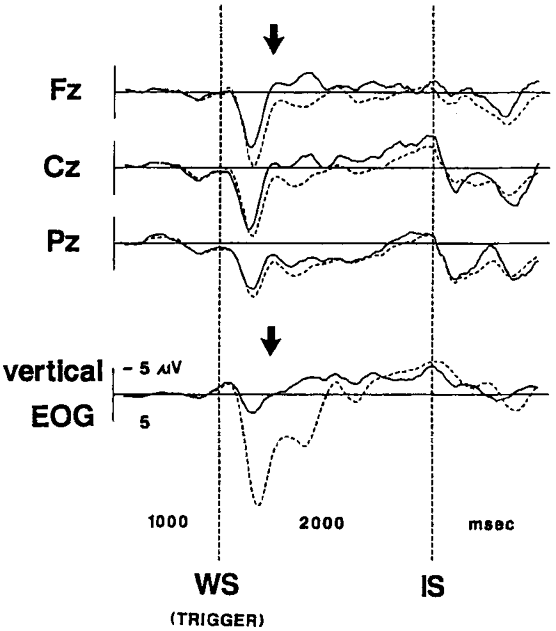

Figure 1. Median waves (solid lines) and average waves (dashed lines) calculated by using 30 trial data of 1 subject. WS, warning stimulus; IS, imperative stimulus. The arrows indicate large difference between both waves. (From "Median Method for Detecting Endogenous Event-Related Brain Potentials," by H. Yabe, F. Saito, and Y. Fukushima, 1993, *Electroencephalography and Clinical Neurophysiology*, *89*, p. 406. Copyright 1993 by Elsevier Science, Ltd. Reprinted with permission.)

These findings, however, do not imply that an EOG correction procedure in the median method is unnecessary. The median method is more effective after the application of the EOG rejection.

Trial-to-Trial Variation of Brain Signals Themselves

This phenomenon concerns the major premise of the average method—that is, the presupposition that the signals are invariant across every trial. This assumption of signal constancy seems unlikely, because two kinds of fluctuations in brain activity may generate variation in the amplitude and/or latency of the signal. One is the fluctuation of the psychological state. As Ruchkin (1988) has indicated, psychological factors—such as fatigue, habituation, the attention of the subject, or all of these—can affect ERPs. Even if the stimulus in every trial is identical, the fluctuation of his or her mental state can lead to random trial-to-trial variations in the amplitude, the latency of the brain signal, or both. In contrast

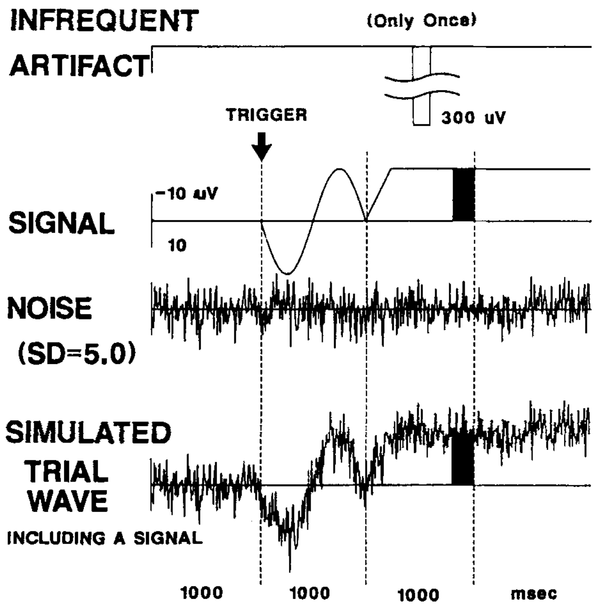

Figure 2A. Simulated trial data. Top: an infrequent artifact (occurred only once, 300 μV). Middle: a signal wave (maximum amplitude is 20.0 μV) and a noise wave (when noise amplitude *SD* is 5.0 μV). Bottom: a simulated trial wave including a signal. (From "Median Method for Detecting Endogenous Event-Related Brain Potentials," by H. Yabe, F. Saito, and Y. Fukushima, 1993, *Electroencephalography and Clinical Neurophysiology*, *89*, p. 404. Copyright 1993 by Elsevier Science, Ltd. Reprinted with permission.)

to endogenous ERP, an exogenous evoked potential (EP), such as the auditory brain stem response, should be influenced very little by mental fluctuation. Even in EP, however, another putative variation may be derived from the fluctuation in the membrane potentials of the generator neurons (Ruchkin, 1988).

Extreme Case of Signal Variation in Both Amplitude and Latency: Lack of Signal in Some Trials

The lack of a signal in some trials can be regarded as the extreme case of variation in the amplitude and latency of the signal, because the extreme reduction of signal amplitude, the remarkable deviation of signal latency, or both can also lead to the lack of a signal. It is realistic to assume that the psychological processes that generate the endogenous signals may be missing in some trials. Picton and Hillyard (1988) proposed that the task relevance of the stimulus is a determinant of the endogenous ERP and that the subject might ignore the stimulus and attend to something else. In order to avoid this problem, some experimenters may take precautions—for example, requiring the subject to press a button for each target response that is to be included in the calculation of the ERP, or pausing the experiment to check the sum of counted responses. However, such precautions are available only for simple task performance. Thus, the assumption that the psychological process occurs constantly in every trial is tenuous, even when all measurements are obtained under similar experimental conditions.

The median method is effective when some signals are lacking, even if the number of data is small and their distribution is non-Gaussian (Yabe et al., 1993). Figures 2A–2D illustrate this effect for the omitted signals. Artificial signals were combined to simulate ERP trials (Figure 2A). The invariant signals were included in a fraction of all trials (F_s). The percentage of signal occurrence ranged from 0/30 to 30/30 (i.e., 0%–100% of F_s). Using the central limit theorem, zero-mean Gaussian random data were included in every trial in order to simulate noise. The standard deviations of these noise amplitudes (*SD*-noise) were varied from 0 to 20 μV. The median wave—as well as the average wave—was calculated from the 30 simulated trial data. Figure 2B illustrates two waves elicited by each method when F_s was 70%. The figure indicates that the hidden signal amplitudes were reproduced more clearly with the median method than with the average method. In addition, the median waves are influenced very little by an infrequent artifact.

The time mean amplitudes were measured across the interval shown by the closed rectangles in Figure 2A. These amplitude values for each method were plotted.

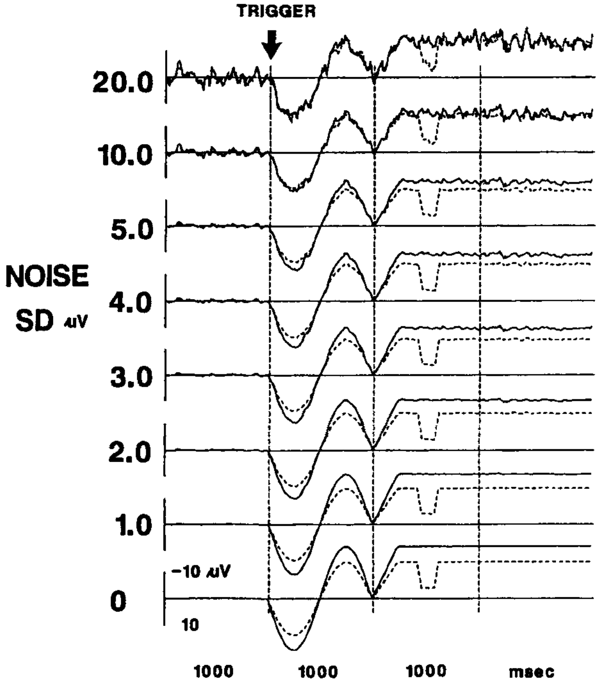

Figure 2B. Median waves (solid lines) and average waves (dashed lines) for every *SD*-noise at 70% point of F_s. Median amplitudes are larger than averaged ones. Median waves are little influenced by infrequent artifact. (From "Median Method for Detecting Endogenous Event-Related Brain Potentials," by H. Yabe, F. Saito, and Y. Fukushima, 1993, *Electroencephalography and Clinical Neurophysiology*, *89*, p. 405. Copyright 1993 by Elsevier Science, Ltd. Reprinted with permission.)

The averaged amplitudes increased in proportion to F_s, as is shown in Figure 2C (top). The curves of the median amplitudes varied from linear to rectangular as the standard deviation of the noise (*SD*-noise) decreased, as is shown in Figure 2C (bottom). When F_s was larger than 50%, the median amplitudes tended to be larger than the averaged amplitudes. Thus, the median method was more sensitive to the probable signal with a larger percentage of signal occurrence than was the average method. The median method exhibited a strong ability to detect the hidden signals. In addition, the smaller the *SD*-noise, the greater this ability. On the other hand, when F_s was smaller than 50%, the median amplitudes tended to be smaller than the averaged ones. That is, an infrequent artifact such as eye movement had less effect on the median ERPs than on the averaged ERPs, in which the signal was replaced by the artifact. Consequently, the relationship among the signal amplitudes, *SD*-noise, and F_s could be approximately represented by the equation at the bottom of the page.[1]

In addition, the different effect between the median and the average methods should be related to the distribution of data. Skewness, kurtosis, and *SD* have been estimated on every time point. As is shown in Figure 2D, the large difference between both methods corresponds to the large deflection of *SD*, kurtosis, and skewness.

Trial-to-Trial Variation in Signal Amplitude

Under conditions where the data set of all trials includes no infrequent artifact and no signal omission, the trial-to-trial variation of signal amplitude at each time point can be Gaussian distributed. In the case of Gaussian-distributed data, the average values appropriately express the central tendency of the group of data at any time point, which suggests that the averaged waveform should be similar to the median one.

Trial-to-Trial Variation in Signal Latency

The most troublesome problem is that of signal latency jitter, which has been disclosed by the single-trial ERP studies (Kerkhof & Uhlenbroek, 1981; Michalewski et al., 1986; Pfefferbaum et al., 1984a, 1984b). This section addresses the problem of variation in the response latency and discusses the procedure for applying the median method to data sets with jittered latency.

The trial-to-trial latency jitter of the signal is very difficult to eliminate by using the average method, because it introduces obscure error into the average ERP measurements. As Ruchkin (1988) has indicated, the average wave will be different from the waveform of the underlying signal because of the jittering in signal latency, although it will approach that of the signal as the number in the average increases.

One solution is to employ the latency-corrected averages, as in Woody's (1967) method. According to Ruchkin (1988), the computation of latency-corrected averages requires "filtering to attenuate noise," "estimation of the signal latency for each trial," and "compensation for the latency shift before averaging." For example, Woody's method uses adaptive correlation detection. The latency for each ERP is estimated by computing the cross-correlation function between the ERP waveform and a waveform template that is an estimate of the signal waveshape. However, it is known that this method has a problem in introducing overestimation of latency variability and signal amplitude. The most significant problems with Woody's method are that it can produce plausible signals even from noise-only data (Ruchkin, 1988)

$$\text{Median Amplitude} = V \cdot \left(\frac{\left(SD/V + \sqrt{\pi \cdot X^2}\right) \cdot \left(SD/V - \sqrt{X^2}\right) + \sqrt{\pi} \cdot X^2 + 1}{\left(SD/V + \sqrt{\pi \cdot X^2}\right) \cdot \left(SD/V - \sqrt{X^2}\right) + \sqrt{\pi} \cdot X^2 + \sqrt{X^2}} \cdot X + 1 \right),$$

where

$$V = \text{Signal Amplitude} / 2 \qquad [\mu V],$$

$$SD = \text{Standard Deviation of Noise Amplitude} \qquad [\mu V],$$

$$X = 2 \cdot F_s - 1 \quad (-1 \le X \le 1),$$

$$0 \le \left(F_s = \frac{\text{Number of Trials including a Signal}}{\text{Number of Total Trials}} \right) \le 1,$$

$$SD \to 0: \text{ Median Amplitude} \to V \cdot \left(\frac{X}{\sqrt{X^2}} + 1 \right),$$

$$SD \to +\infty: \text{ Median Amplitude} \to V \cdot (X + 1) = (\text{Signal Amplitude}) \cdot F_s,$$

$$= \text{Averaged Amplitude}.$$

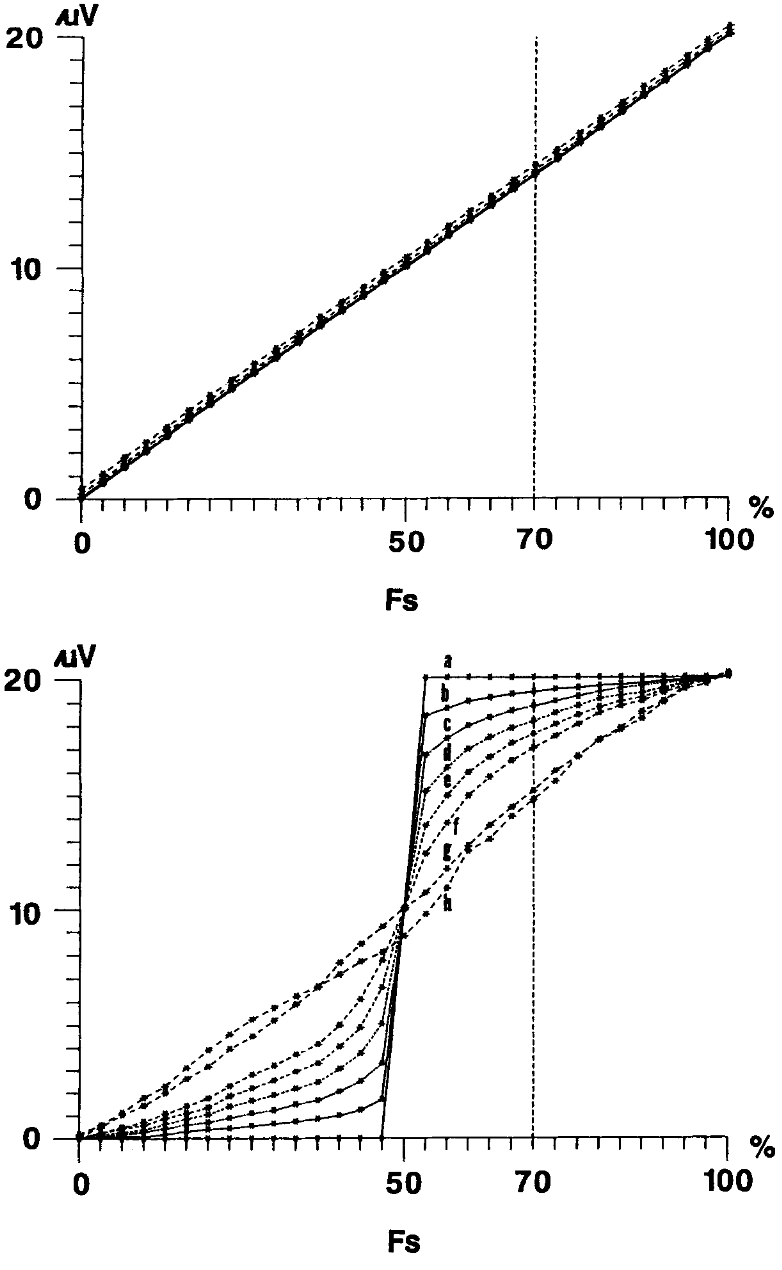

Figure 2C. Top: relationship between the average amplitudes (vertical axis) and the fraction of trials including the desired signals (F_s; horizontal axis). Bottom: relationship between the median amplitudes (vertical axis) and F_s (horizontal axis). Alphabetical abbreviations indicate different noise *SD*s: a = 0, b = 1.0, c = 2.0, d = 3.0, e = 4.0, f = 5.0, g = 10.0, h = 20.0 µV. (From "Median Method for Detecting Endogenous Event-Related Brain Potentials," by H. Yabe, F. Saito, and Y. Fukushima, 1993, *Electroencephalography and Clinical Neurophysiology*, *89*, p. 405. Copyright 1993 by Elsevier Science, Ltd. Reprinted with permission.)

or that the template used in cross-correlation techniques may "lock on" to some other prominent EEG (Puce, Berlovic, Cadusch, & Bladin, 1994). It must be noted that the usual techniques of single-trial ERP also depend on the cross-correlation function (Puce et al., 1994).

We found that the waveform that was generated by the median method was less affected by this jittering than was that generated by the average method (Yabe et al., 1998). This effect was clarified by applying the median method for the simulation of trial-to-trial latency jitter.

Simulation Using Artificial Data

Artificial signals were combined in order to simulate ERP trials. The signal wave in each trial was composed

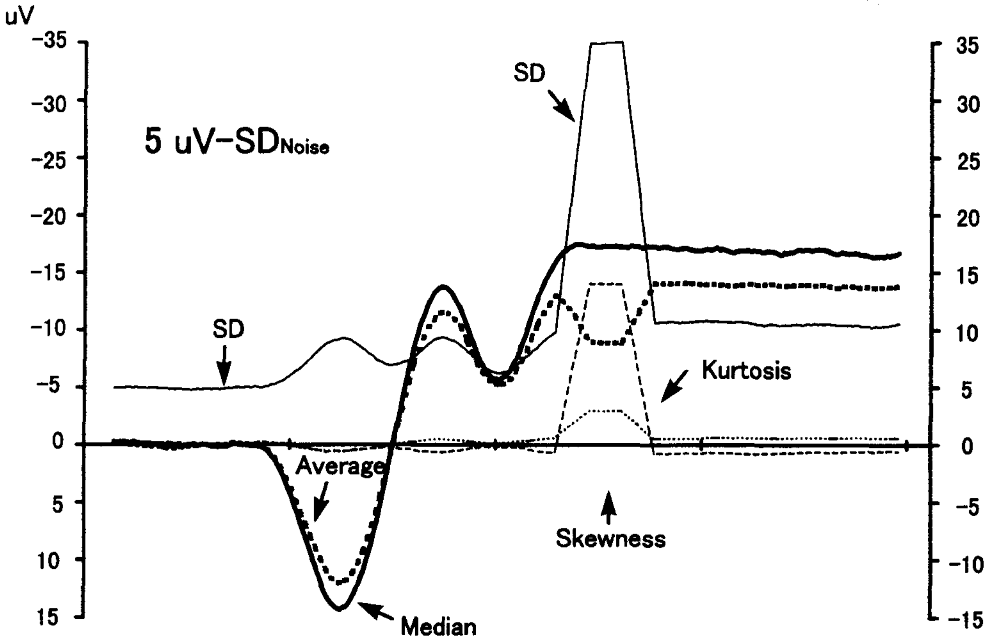

Figure 2D. Median (thick, solid line; left axis), average (thick, dotted; left axis), skewness (thin, dotted; right axis), kurtosis (thin, dashed; right axis), and *SD* (thin, solid; right axis) waves for 5 μV *SD*-noise at 70% point of F_s.

of a sine wave, a triangular wave, and a rectangular wave. To simulate the trial-to-trial latency jitter of the signal, each signal latency was shifted back or forward in time, in accordance with a Gaussian-distributed time lag produced by the central limit theorem, with standard deviations of time lag (*SD*-latency) of 0.08 cycle (small jittering) or 0.16 cycle (large jittering), when one cycle of a sine wave—a component of the artificial signal—was regarded as 1.0 cycle. In addition, using the central limit theorem, zero-mean Gaussian random data were included in every trial in order to simulate the background noise. The standard deviations of these noise amplitudes (*SD*-noise) were varied from 0 to 20.0 μV. Figure 3 indicates that the signal amplitudes were reproduced more clearly with the median method than with the average method.

Simulation Using Actual Data

One subject (a 28-year-old male) was studied in an electrically shielded room during an auditory oddball paradigm. Approximately 900 stimuli, consisting of sinusoidal tone bursts (duration 100 msec, including 10-msec rise and fall times), were presented at an intensity of 70 dB SPL with a stimulus onset asynchrony (SOA) of 2 sec. Tone bursts were either high (2000 Hz, $p = .1$) or low (1000 Hz, $p = .9$). The subject was instructed to listen to the series of tones and to respond to high tones by pushing a button as quickly as possible. EEG was recorded with silver–silver chloride disc electrodes from Fz, Cz, Pz, and Oz. The vertical and horizontal EOGs were also measured. The interelectrode impedance was reduced to below 5 kΩ. The analysis period was 1,024 msec (sampling rate 500 Hz), including a prestimulus baseline of 250 msec. After baseline subtraction, the trial data associated with EOG amplitudes exceeding ±75 μV were rejected. Consequently, 87 trial data for the target stimuli were obtained. Two kinds of simulations that used these trial data were performed for trial-to-trial latency jittering, as follows.

Simulation A. Beforehand, the P300 response (Sutton, Braren, Zubin, & John, 1965) was calculated by simply averaging 87-trial data at Cz. The resulting response was assumed to be a true P300 signal in the brain. To simulate trial-to-trial latency jitter, this response was shifted back or forward in time (i.e., artificially jittered) with the different standard deviations of time lag (*SD*-latency) from 10 to 45 msec, as is shown in Figure 4. These jittered latencies were Gaussian distributed by using the central limit theorem. Then both the average and median methods were applied to these trial data. Two waves calculated by each method are shown in Figure 5. The figure indicates that the signals were reproduced more clearly by using the median method than by using the average method, which indicates that the median waves were less influenced by trial-to-trial latency jitter.

Simulation B. The original 87 trials at Cz were artificially and randomly jittered with the different standard deviations of time lag (*SD*-latency) from 10 to 80 msec. In this case, it was not clear whether the distribution of the signal latencies was Gaussian, because each original

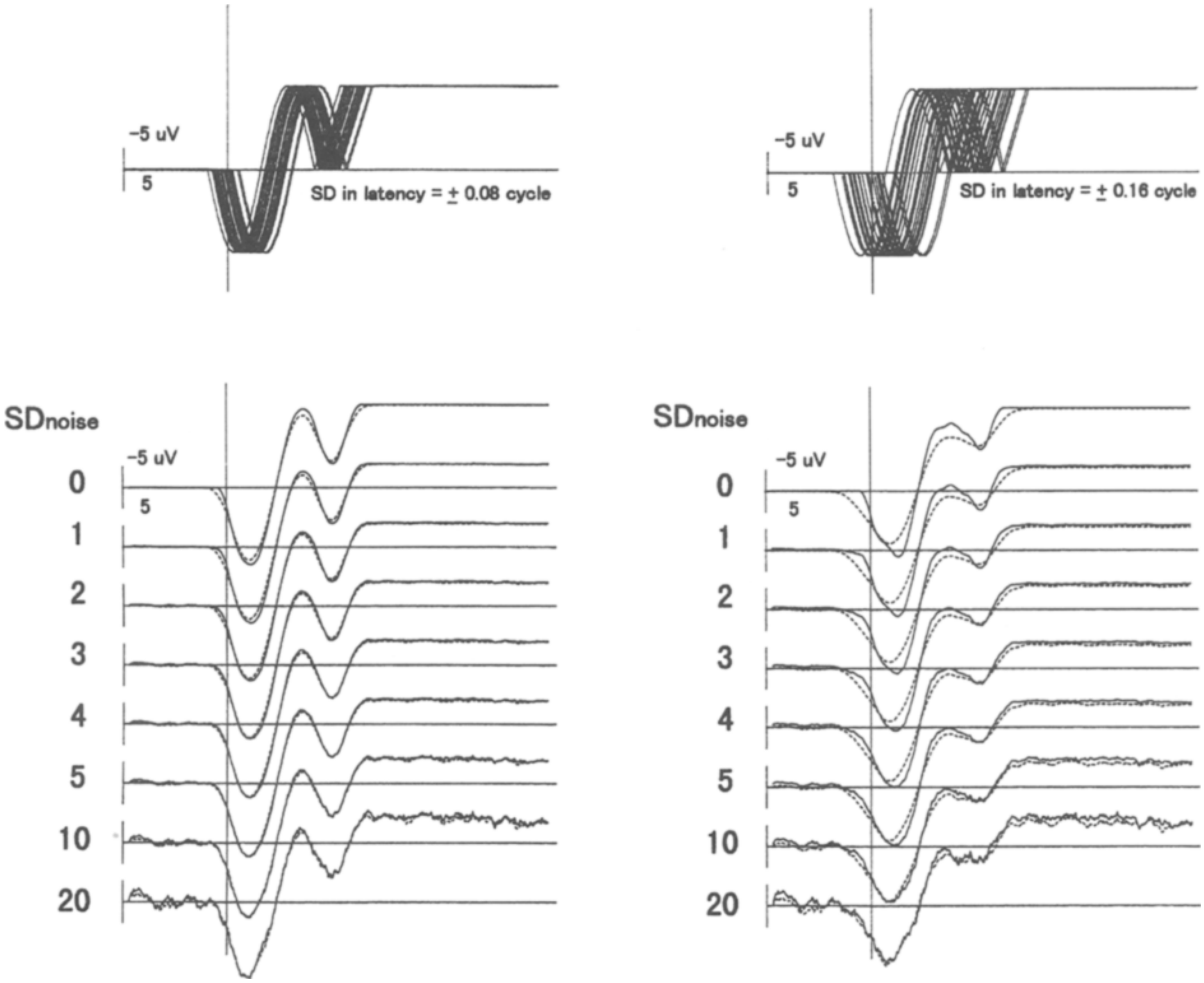

Figure 3. Simulation of trial-to-trial latency jitter for the artificial data. Top: superimposition of 30-trial ERPs jittering with *SD*-latency of 0.08 cycle (left) and 0.16 cycle (right), when one cycle of sine-wave component is regarded as 1.0 cycle. Bottom: the median waves (solid lines) and average waves (dashed lines) for each *SD*-noise with latency jittering of *SD*-latency of 0.08 cycle (left) and 0.16 cycle (right). (From "The Effect of Median Method on the Trial-to-Trial Latency Jitter of ERP Signals," by H. Yabe et al., 1998.)

trial itself may have had some degree of latency jittering. As in Simulation A, both the average and the median methods were applied to these trial data. Two waves that were calculated by each method are shown in Figure 6. In this figure, the signal amplitudes are larger with the median method than with the average method. This also indicates the effect of the median method on the problem of trial-to-trial latency jitter.

As is shown in Figures 5 and 6, the median waves are less influenced by latency variation. With larger as well as with smaller variation in latency, however, there are smaller differences between the median waves and the average ones. Thus, the effect of the median method on latency jitter is limited to some range of variation in latency. If the median method is applied together with the latency-corrected methods—such as the Woody (1967) method—the real signals could be identified more precisely.

Additionally, the effect of the median method for latency jitter should also be related to the distribution of data. Skewness, kurtosis, and *SD* have been estimated on every time point for the data of 30-msec *SD*-latency produced in Simulation A. As is shown in Figure 7, the large difference between the median and the average waves almost corresponds to the large deflection of *SD*, kurtosis, and skewness.

Conclusion

Many researchers have used the average method to identify ERPs. However, the signal detection performance of averaging will be degraded if the signal is non-invariant—for example, due to the instability of the signal—and the noise is variable. Ruchkin (1988) described two types of possible signal variation in amplitude and in latency. The median method can address the problems that are encoun-

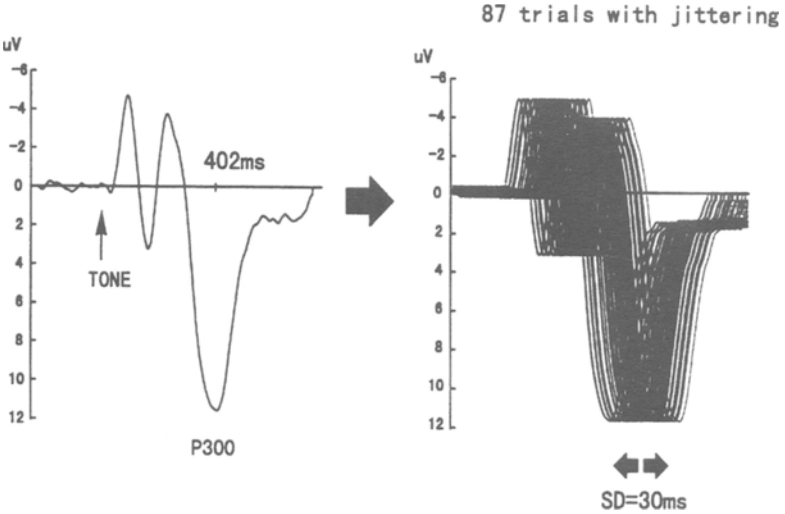

Figure 4. Simulation of trial-to-trial latency jitter for the actual data. Left: P300 response calculated by averaging 87-trial data at Cz. Right: superimposition of 87-trial data artificially jittered in latency with *SD*-latency of 30 msec. (From "The Effect of Median Method on the Trial-to-Trial Latency Jitter of ERP Signals," by H. Yabe et al., 1998.)

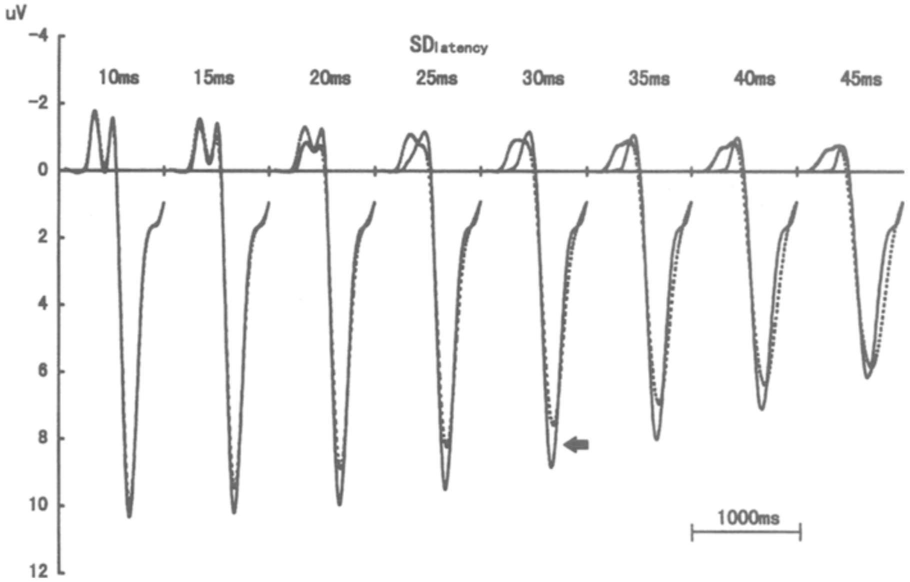

Figure 5. Simulated latency jitter using P300 response calculated by simply averaging 87-trial data at Cz. Median (solid lines) and average waveforms (dashed lines) for every *SD*-latency. The arrow indicates largest difference between both waveforms. (From "The Effect of Median Method on the Trial-to-Trial Latency Jitter of ERP Signals," by H. Yabe et al., 1998.)

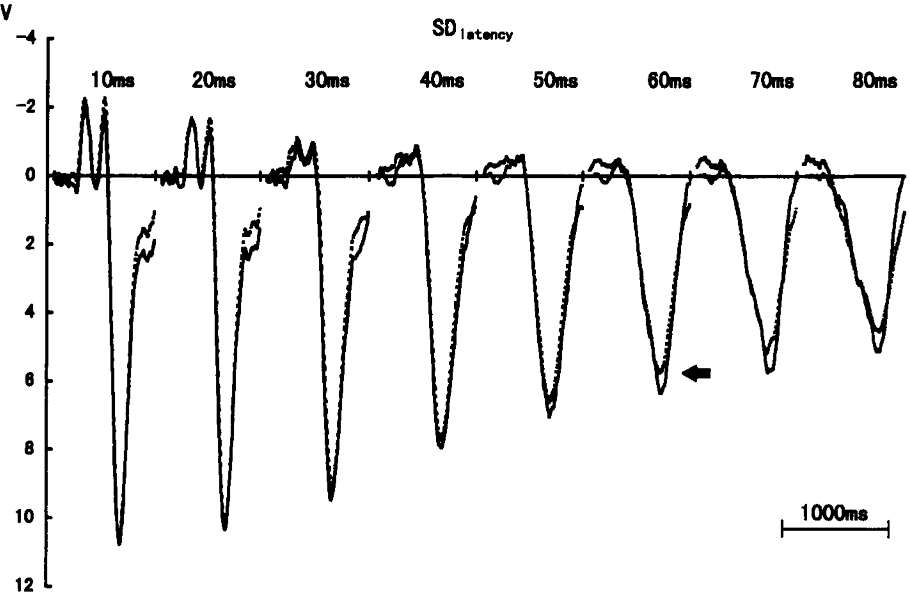

Figure 6. Simulated latency jitter using the original 87-trial data at Cz. Median (solid lines) and average waveforms (dashed lines) for every *SD*-latency. The arrow indicates largest difference between both waveforms. (From "The Effect of Median Method on the Trial-to-Trial Latency Jitter of ERP Signals," by H. Yabe et al., 1998.)

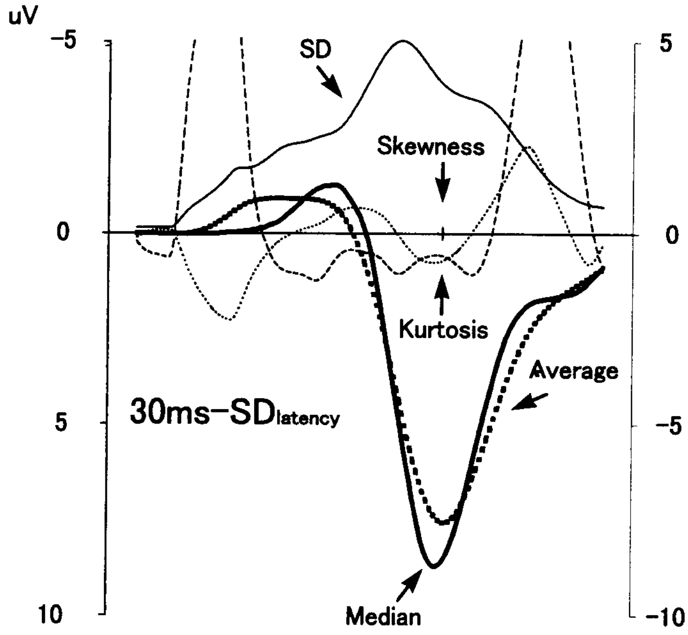

Figure 7. Median (thick, solid line; left axis), average (thick, dotted line; left axis), skewness (thin, dotted line; right axis), kurtosis (thin, dashed line; right axis), and *SD* (thin, solid line; right axis) waves for 30-msec *SD*-latency at Cz. (From "The Effect of Median Method on the Trial-to-Trial Latency Jitter of ERP Signals," by H. Yabe et al., 1998.)

tered in the application of the average method as follows. First, the median method is valid even when applied to small amounts of data, non-Gaussian data, or both. Second, the median wave is less distorted than is the averaged one by an infrequent artifact. Third, the median method is effective for the extreme variations—for example, the lack of some signals. Finally, the trial-to-trial variation in signal latency is very difficult to eliminate, which introduces systematic error into the average ERP amplitude measurements. The waveform that is generated by the median method is less affected by the trial-to-trial signal latency jitter than is that generated by the average method.

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NOTE

1. From "Median Method for Detecting Endogenous Event-Related Brain Potentials," by H. Yabe, F. Saito, and Y. Fukushima, 1993, *Electroencephalography and Clinical Neurophysiology*, **89**, p. 405. Copyright 1993 by Elsevier Science, Ltd. Adapted with permission.

APPENDIX
Computational Procedure of Median Method

Unlike Borda and Frost's (1968) method, the present median method requires that every trial be corrected on the basis of a baseline, before the median value on each time point is calculated, in order to eliminate the baseline shift that is produced by the sustained artifacts. After being sorted in the order of amplitude at each time point, all of the data for a given time point are ranked among all N trials. Let $R_k(t)$ be the amplitude which is baseline corrected in every trial and ranked for every time point, where t is the tth sample (from 1st to Tth) and k is the kth number of amplitude rank (from 1st to Nth). A set of amplitude data obtained in each rank are defined as follows:

$$\begin{aligned} 1\text{st rank data} &= \{R_1(1), R_1(2), , R_1(t), , R_1(T)\} \\ 2\text{nd rank data} &= \{R_2(1), R_2(2), , R_2(t), , R_2(T)\} \\ &\vdots \\ k\text{th rank data} &= \{R_k(1), R_k(2), , R_k(t), , R_k(T)\} \\ &\vdots \\ N\text{th rank data} &= \{R_N(1), R_N(2), , R_N(t), , R_N(T)\}. \end{aligned}$$

Consequently, the median wave is defined as follows:

If N is odd,

$$\text{Median wave} = \{R_{(N+1)/2}(1), R_{(N+1)/2}(2), , R_{(N+1)/2}(t), , R_{(N+1)/2}(T)\}.$$

If N is even,

$$\text{Median wave} = \{(R_{N/2}(1) + R_{(N/2)+1}(1))/2, (R_{N/2}(2) + R_{(N/2)+1}(2))/2, , (R_{N/2}(t) + R_{(N/2)+1}(t))/2, , (R_{N/2}(T)+R_{(N/2)+1}(T))/2\}.$$