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Authors

Michalewski, HJ
Mohamed Kamel, AW
Starr, A

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Brain potentials during mental distance judgments

Henry J. Michalewski¹, Abdel-Wahab Mohamed Kamel² and A. Starr¹

¹ *Department of Neurology, University of California, Irvine, CA 92717 (U.S.A.)*

and ² *Department of Psychology, Tanta University, Tanta (Egypt)*

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Visual event-related potentials were recorded from a group of 10 normal subjects while they judged the proximity of two letters of the alphabet. Subjects viewed singly the letters A, D, G, L, N, T, W and Z and indicated by button press whether the letter displayed occurred before or after the comparison letter M. Reaction times to close letters (L and N) were longer than ordinarily more distant letters (A, D, G, T, W, Z). A late parietally positive potential of approximately 475 ms covaried in latency and amplitude with these judgments. Late potentials were delayed in latency and reduced in amplitude to close letter (L and N) judgments compared to the other letters. The results suggest that mental processes, such as alphabetic distance judgments, may be usefully studied by examining their associated event-related potentials.

INTRODUCTION

When individuals are asked to judge which of a pair of digits is larger, their decision time is a function of the numerical size or distance between the numbers (Moyer and Dumais, 1978; Moyer and Landauer, 1967). Reaction times (RTs), for instance, are longer when the difference between the number pair is small as when, for example, subjects are asked to judge which is larger 7 or 8 (difference is equal to one) compared to the shorter RTs when the difference between the pair of numbers is greater, for example, 1 or 9 (difference is equal to eight). The decision time discrepancy between the longer and shorter RTs in simple judgments of this type is known as the distance effect. The exact cognitive mechanisms operating that might account for the distance effect are unresolved but are likely to involve classification and organization processes along the judged di-

mension, and memory. The distance effect has been extended to include other types of ordered magnitude estimations including judgments of animal sizes (Moyer, 1973), and common everyday objects (Paivio, 1975). In these instances, the distance effect presumably was working through some relative magnitude estimate assigned by the subject at the time of the judgment, or a memory-coded representation based on size. Distance effects are also found in symbolic judgments in which the dimension being compared is much less apparent, such as the alphabetic separation of letter pairs (Lovelace and Snodgrass, 1971; Parkman, 1971). It is of interest to note that ordered distance judgments are particularly resistant to repetition, and distance can persist for thousands of test trials (see, for example, the experiments reported by Banks and White, 1982).

Inferences about the cognitive operations involved in producing distance effects have relied exclusively on behavioral measures such as RT. We were interested in examining the cortical activity during such judgments to determine if electrophysiological measures provided any additional

Correspondence: H.J. Michalewski, Department of Neurology, University of California, Irvine, CA 92717, U.S.A.

information about the brain processes involved. In particular, the late positive P300 or P3 potential appears as a likely candidate to reflect the distance effect since this wave has been shown to be sensitive to processes such as stimulus evaluation (Donchin, 1979; Donchin et al., 1978; Kutas et al., 1977; Magliero et al., 1984; McCarthy and Donchin, 1981) and memory (Ford et al., 1979). For example, task situations involving difficult discriminations prolong the latency of P3 compared to easier discriminations (Ford et al., 1976; Goodin et al., 1983; McCarthy and Donchin, 1981). Variations in the amplitude of P3 also appear to reflect certain cognitive processes associated with stimulus probability, task demands, task complexity (e.g. Donchin et al., 1978; Isreal et al., 1980), and anticipated task difficulty (Ullsperger et al., 1987).

In the study detailed below we investigated the effects of judging ordinal letter position in the alphabet and the relationships that these decisions have to the latency and amplitude of the late positive potential.

MATERIALS AND METHODS

Subjects

A normal group of 10 individuals (3 males, 7 females; mean age = 19.4 years) was recruited and tested from the campus of the University of California, Irvine. Subjects received class credit and were paid for their participation in the experiment. All were right-handed and had either normal or corrected-to-normal vision.

Stimulus materials and procedures

Subjects viewed single the letters A, D, G, L, N, T, W and Z, presented for a duration of 50 ms every 2–3 s on a raster-synchronized video monitor. The letters were microcomputer-generated and fell within a bounded visual angle of 0.7 degrees. Each letter was presented 40 times in an order that was pseudorandomly determined with the restriction that no letter was allowed more than 3 successive repetitions. The distance judgment consisted of deciding whether the letter displayed occurred before (press left) or after (press right)

the letter M in the alphabet. Thus, subjects were making an ordinal position judgment comparing the test letter with the letter held in memory (M) on each trial. Measures of RT were made from the onset of the test letter to the time when a button was pressed. Before testing began, subjects were given practice to insure an understanding of the task, and were instructed to respond quickly and accurately while maintaining visual fixation in order to minimize eye movements. The subjects were seated in a comfortable armchair inside a sound-attenuating chamber during electrode application, practice, and testing.

Our method of stimulus presentation for eliciting distance effects differs in some respects from conventional procedures (1) by presenting only one stimulus test item per trial for judgment, and (2) by having only a single fixed comparison letter (the letter M) throughout. We hypothesized that the letters A, D, G, and L were ordinally decreasing in distance to the comparison letter M, respectively, whereas the letters N, T, W, and Z were increasing in distance from the letter M, respectively. Thus, the separation between letters A and M, for example, was greater than the distance between letters L and M.

Recording

Scalp EEG was recorded from midline electrode sites Fz, Cz, and Pz referenced to linked earlobes. Additional electrodes were affixed above and at the outer canthus of the right eye to monitor eye movements. A ground electrode was placed on the forehead. Electrode impedances were measured at or below 3.0 k Ω .

The potentials from each recording site were differentially amplified (2.0×10^5 for EEG; 1.0×10^5 the eye channel) with Grass P511J amplifiers using a bandpass of 0.1–100 Hz (3 dB down, 6 dB/octave slopes). The potentials from the 3 midline scalp electrodes and eye movement monitor were sampled and stored on disc as single trials for each stimulus letter. The sweep time was 1.0 s (dwell time = 3.9 ms) beginning 200 ms before stimulus onset. Each channel consisted of 256 digitized points. Averaging of the evoked potentials was performed off-line using a DEC MINC 11/23 + computer.

Evoked potential averages

Conventional averages. Average evoked potentials for each letter were computed. Trials with incorrect responses or an eye channel exceeding 100 μ V were excluded from analysis. Measurements of peak amplitude and latency of the late positive potential were made from digitally filtered averages (bandpass equivalent to 0–37.5 Hz, 3 dB down at 37.5). The late potential was defined as the maximum positivity in a given derivation following the initial N1-P2-N2 sequence.

Latency adjusted averages. Late potential activity was analyzed on a single trial basis using a correlational-template procedure (Woody, 1967). This analysis allowed us (1) to estimate latency variability of the late potential during close compared to more distant letter judgments, (2) to derive a corrected amplitude measure of the late potential with latency jitter removed, and (3) to compute the relationship between late potential latency and reaction time. Briefly, a separate late potential template was defined from each subject's conventional average to each letter. The template encompassed the region of the late potential beginning at N2, proceeding to the maximum positivity, and following symmetrically to a point on the downward limb of the late potential. Each template waveshape (consisting of 64 data points) was then used to scan the single trial EEG searching for a similar waveform. Correlations between the points comprising the template and a corresponding region of the EEG were computed as the template was moved along the single trial. The point of maximum correlation between the template and single trial was used to identify the late potential. Peak latency on a single trial was determined by knowing how far the template was moved (lagged) to the point of maximum correlation. A template window of 350 ms was used to scan for the late potential. The template was positioned ahead of the expected late potential so that the initial correlations were low (template out of phase with single trial EEG) and increased as the template was lagged toward the late potential. The starting position of the template was adjusted individually for each subject based on the peak latency determined for each letter from conventional averages. A corrected average was com-

puted by summing the points comprising the detected peak and divided by the number of trials. A corrected peak amplitude was then calculated from the maximum positivity to baseline. The single trial analysis was carried out for each of the midline electrode derivations. The single trials analyzed corresponded to the accepted trials entered into the conventional averages; the single trial was digitally filtered to attenuate higher frequencies (bandpass equivalent to 0–37.5 Hz, 3 dB down at 37.5) prior to performing the correlations. Additional details regarding the single trial procedures applied here and the restrictions imposed by using these techniques have been described in a previous report (Michalewski et al., 1986).

Data reduction and analysis

Mean RTs to correct responses, number of errors, peak latencies and amplitudes, and adjusted peak amplitudes were separately analyzed using two-factor (letters $\times$ electrodes) analysis of variance procedures for repeated measures. Correlation coefficients were computed between the estimated single trial latencies of the late potential and reaction time at Pz for each stimulus letter for each subject. Correlations were *z*-transformed prior to analysis. Transformed values were entered into a single-factor (letters) repeated measures analysis of variance. Post-hoc tests of the means were conducted using the Tukey test (Keppel, 1973). Significance levels were set at $P < 0.05$, or better.

RESULTS

Behavioral responses

Reaction time and error rates. The distribution pattern of RTs to correct judgments suggested an alphabetic distance effect ($F_{7,63} = 8.0$, $P < 0.001$). Mean RTs and standard errors (S.E.M.) to each letter for the entire group of subjects are shown in Fig. 1A. The RTs to letters L and N, ordinarily the closest letters to the comparison letter M, were longer compared to the other letters either before or after. Post-hoc tests indicated that RTs for the letter N were significantly longer than either A, D, G, T, W, or Z; RTs for L were similarly longer

Fig. 1. Mean reaction times (A) and mean number of errors (B) to each letter for the group of subjects.

than for the other letters but only the differences between L and A attained significant levels. None of the remaining differences among letter combinations was significant.

The errors made by subjects also appeared to reflect distance effects ($F_{7,63} = 7.8$, $P < 0.001$). The mean number of errors and S.E.M.s are below in Fig. 1B. More errors were made to L than either A, D, G, T, W, or Z. The ordinally close letter N similarly displayed more errors but differences only reached significance for A, W, and Z. None of the remaining differences among letter combinations was significant.

Evoked potentials

Peak latency. An ordinal symbolic distance effect was evident for the latency of the late potential. Means and S.E.M.s based on measures derived from the conventional averages are shown in Fig. 2A for the parietal derivation. Peak latencies to the letters L and N were generally longer to the comparison letter M than the latencies of the more ordinally distant letters. Latency differences among letters were restricted to main effects ($F_{7,63} = 12.4$, $P < 0.001$) and did not appear affected by electrode location (electrodes, $F_{12,18} < 1$; letters $\times$ electrode interaction, $F_{14,126} = 1.3$). Post-hoc tests

indicated that late potential latencies for L and N were longer than the latencies for the most distant letters A or Z.

Latency variability. An analysis of late component variability derived from the peak latencies estimated from the single trials was performed. Significant effects for letters ($F_{7,63} = 3.9$, $P < 0.001$), electrodes ($F_{2,18} = 20.3$, $P < 0.001$), and an interaction of these variables was indicated (letters $\times$ electrodes, $F_{14,126} = 1.9$, $P < 0.037$). Analysis of the interaction showed that peak variability at Fz and Cz sites did not differ significantly among the test letters, whereas at Pz some distance effects

were found. At Pz the latency variability of close letters L and N was larger than for the more distant letter A; other differences reaching significant level indicated that the variability of letters D and Z was also larger than A. Variability differences between letters L and N were not significant, nor were any other differences among letter combinations significant. A representation of the latency variability among the letters for Pz is shown in the bottom of Fig. 2B.

Late potential amplitude (conventional). Distance effects appeared in the amplitudes of the late potential. Smaller potentials were recorded to close

Fig. 2. Mean late potential latency (A) based on conventional measures and average standard deviation (B) based on the latencies determined from single trials for each subject.

Fig. 3. Mean late potential amplitude for both conventional averages (A) and corrected averages (B).

letters L and N than to the other letters. Significant amplitude effects for letters ($F_{7,63} = 4.5$, $P < 0.001$), electrodes ($F_{2,8} = 21.0$, $P < 0.001$), and an interaction of these variables was indicated (letters $\times$ electrodes, $F_{14,126} = 2.0$, $P < 0.02$). Analysis of the interaction showed that distance effects were more prominent at the parietal than either frontal or central derivations. Mean amplitudes of the late potential at Pz are shown in Fig. 3A. For the Pz derivation, late potential amplitudes were significantly smaller for close letters L and N than for the more distant letters A or Z; the letter N was also smaller than the letter T. For Cz and Fz sites,

there was a similar pattern of amplitude reduction for the ordinally closer letters L and N but the number of differences attaining significance was smaller than for Pz. At Cz, letters N and W were reduced in amplitude compared to letter A; at Fz, the late potentials to letters L and N were smaller than to letter A.

Late potential amplitude (corrected). Late potential amplitudes corrected for latency jitter showed a distance effect but reduced from conventional (uncorrected) amplitude measures. Effects for corrected late potential amplitudes were indicated for letters ($F_{7,63} = 2.4$, $P < 0.03$), electrodes ($F_{2,18} =$

Fig. 4. Overlaid average waveforms for each subject to letters A, L, N, and Z; grand averages appear below. Note the relatively prolonged latencies and reduced amplitudes of the late potential to the ordinarily close letters L and N compared to the average potentials of the more distant letters A and Z.

17.6, $P < 0.001$), and an interaction of letters and electrodes ($F_{14,126} = 2.8$, $P < 0.001$). The corrected mean amplitudes and S.E.M.s for the group for each letter are shown in Fig. 3B for the Pz derivation. The latency adjustment procedure as expected increased the overall amplitudes of the late potential for all electrode sites. The distance effects, however, were no longer evident after the amplitude adjustment procedure at the frontal and central locations. At the parietal location the pattern of adjusted amplitudes was similar to that found for the amplitudes based on conventional measures, but with fewer differences between the letters reaching significant levels. At Pz, corrected late potential amplitudes for letters L, N, and W were all reduced in size compared to the letter A. Superimposed waveform averages for each subject at Pz to letters A, L, N, and Z and the corresponding grand averages are illustrated in Fig. 4.

Late component latency and RTs. The correlations between late component latency determined from single trials at Pz and RTs were generally low and did not attain significant levels. The average correlation (r) ranged between 0.14 and 0.26 with no particular pattern emerging between

a correlation value and the relative ordinal position of a letter ($F_{7,63} < 1.0$).

P2 latency and amplitude. An earlier positive component, P2, varying in average latency between 150 and 230 ms, was evident in the individual subject averages and grand average waveforms (Fig. 4). The latencies and amplitudes of this earlier potential were analyzed with conventional measures to determine if distance effects were evident. None of the latency or amplitude measures for P2 reached significance and thus this earlier positive component did not appear to reflect the distance effect.

DISCUSSION

The distribution pattern of RTs and errors confirm an ordinal alphabetic distance effect in our modified version of the symbolic distance paradigm in which only a single item was presented for evaluation and compared to a non-changing letter held in memory. Parietally distributed late potentials were delayed and attenuated to close letter pairs (e.g. L and M, or M and N)

compared to more ordinally distant letter pairs (e.g., A and M, or M and Z). An earlier positive peak in the average potential waveform, P2 (150–230 ms), did not reflect distance effects either in terms of latency or amplitude, and suggests that it was only after P2 that effects of letter comparison emerged. While both RT and late potential latency appeared to covary with ordinal letter position (Figs. 1A and 2A), the relatively low correlations obtained between these measures indicated that RT and latency were not strongly coupled to each other.

Numerous reports in the literature have already demonstrated that increasing perceptual demands increase late potential latency and reduce late potential amplitude. For example, in a recent series of auditory discrimination experiments, Polich (1987) has shown nicely that harder tasks generally increase the latency of the late potential and decrease the amplitude compared to easier tasks. A report by Andreassi and Juszcak (1984) involving visual line length discriminations is of interest here, although the experiment was not designed to study distance judgments. Subjects viewed a 1.0 cm vertical line followed 2 s later by lines of either 0.9 cm, 1.0 or 1.1 cm lengths. Subjects decided whether the second line was shorter or longer than the first. Reaction times as well as late potential latencies were shorter for the 0.9 cm and 1.1 cm line lengths than for the ambiguous 1.0 cm line length. The authors' interpretation suggested that the longer latencies of the late potential were attributable to greater stimulus evaluation time involving ambiguous discriminations. In a sense, the comparison involving the ambiguous lines is analogous to close letter comparisons which may also require extended evaluation times. The difference, however, is that in the alphabetic distance judgments, the increased difficulty of the task is not attributable to approaching the limits of the resolving power of the sensory system, as might occur in either demanding auditory discriminations or differences in line length. While letters of the alphabet may have their own distinctive characteristics for perceptibility, we do not believe that perceptual demand as such accounts fully for the differences reported here, since the letters used were both familiar and easily recognizable.

The reduction in late potential amplitude to close letter pairs observed using conventional averaging procedures differs from the results obtained from amplitudes after the latency adjustment procedure. Ordinal position effects were virtually eliminated from frontal and central derivations after adjustment. This suggests that some of the amplitude reductions observed for conventional averages for close letter judgments resulted from increased latency variability and may reflect extended demands in the evaluation process. Differences in subject strategy, however, may also affect measures of the late potential. Decisions involving letters A or Z, for instance, may be based on their unique end position in the alphabet (with no preceding or following letters, respectively), whereas closer letters as L and N may additionally involve retrieving the ordered relation of the relevant portion of the alphabet. A stimulus letter may thus provide both end point and position information (Potts, 1974). Several subjects employed this sort of mixed strategy even though after questioning they were not always deliberately aware of using either one or the other method of solution. Another factor possibly contributing to component jitter is confidence level. A subject's confidence level may have been higher for the more distant letters than for the close letter pairs. The larger late potentials we observed for distant letters might be accounted for in part by increased confidence levels (e.g. Squires et al., 1975).

The letters used in the present experiment may form a select combination of items restricting our generalization to other groups of letters directly. Indeed, as already suggested, each letter may convey additional information which affects behavior besides ordinal distance. For example, English letter frequencies influence vocal letter RT (Pratt, 1939 cited in Fitts and Switzer, 1962). In another example, Hovancik (1985) showed that earlier portions (or chunks) of the alphabet may be more readily recalled from memory than later portions of the alphabet. Using another group of letters may result in a different pattern of effects than described here but are also likely to involve letters of different ordinal separations. The contribution of different letter sets, letter frequency, position in

the alphabet, and subject factors (e.g. confidence level, gender) to distance judgments requires separate study and consideration.

Thus, these results indicate a close association between the latency and amplitude of the event-related potential components, a parietally positive peak of approximately 475 ms, and the difficulty of judging the proximity of two letters in the alphabet. We are unable to ascertain at what stage along the neural processes of judging letter separation the P475 component may represent. Nevertheless, the correlations defined suggest that the analysis of mental processes utilized in comparison may be benefited by examining their associated event-related potentials.

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