ELSEVIER

Acta Psychologica 94 (1996) 21–40

acta psychologica

Magnitude versus parity in numerical judgements: Event-related brain potentials implicate response conflict as the source of interference [1]

Leun J. Otten [a,*], Padmanabhan Sudevan [b], Gordon D. Logan [c], Michael G.H. Coles [c]

[a] *Cognitive Psychophysiology Laboratory, Department of Psychology, University of Illinois at Urbana-Champaign, 603 East Daniel Street, Champaign, IL 61820, USA*

[b] *Department of Psychology, University of Wisconsin at Stevens Point, Stevens Point, USA*

[c] *Department of Psychology and Beckman Institute, University of Illinois at Urbana-Champaign, Champaign, IL 61820, USA*

Received 7 February 1995; revised 22 July 1995; accepted 1 August 1995

Abstract

When subjects make 'odd/even' and 'low/high' decisions about digits, information about the digit's magnitude can interfere with the decision about the digit's parity. The present experiment used a psychophysiological approach to examine whether this interference arises at the level of response processing. Subjects performed a choice-reaction time task involving low/high and odd/even judgements about the digits 2 through 9. The data point to a response locus for the interference effect with the size of the effect being dependent on the ease with which magnitude information can be used to prime the appropriate response. This, in turn, is influenced by the 'naturalness' of the mapping between magnitude and response hand as well as by the distance of a digit to the low/high cut-point.

PsycINFO classification: 2340; 2300; 2560

Keywords: Number magnitude; Number parity; Locus of interference; P300; Lateralized readiness potential

* Corresponding author. E-mail: lotten@p300.cpl.uiuc.edu.

[1] Some of the data described here were presented at the 10th International Conference on Evoked Potentials, June 1992, Eger (Hungary), and at the 32nd annual meeting of the Society for Psychophysiological Research, October 1992, San Diego, CA, USA.

SSDI 0001-6918(95)00047-X

1. Introduction

Numbers have several properties. They can represent magnitude, can be a prime or not, can be multiples of some other number, or can be odd or even. In a series of studies that manipulated two of these properties, Sudevan and Taylor (1987) showed that when subjects make 'low/high' and 'odd/even' decisions about digits, information about whether a digit is low or high can interfere with the decision as to whether a digit is odd or even. This interference is evident in reaction time and accuracy measures when parity and magnitude judgements involve responses with different hands. The interference is asymmetric, being only evident when parity judgements are made in the presence of conflicting magnitude information, but not vice versa. An interference of magnitude information on parity judgements has also been found when parity judgements are not intermixed with magnitude judgements (Dehaene et al., 1993; Henik and Tzelgov, 1982; Tzelgov et al., 1992). The present experiment uses a psychophysiological approach to examine whether interference from number magnitude on parity judgements arises at the level of response processing, and to determine the influence of spatial response assignment and distance from low/high cut-point on this interference.

In the digit processing task used by Sudevan and Taylor, subjects viewed single digits (2 through 9), surrounded by letters indicating a low/high (LO–HI) or odd/even (OD–EV) decision. If the digit was odd or low, a response had to be given with the left hand. If the digit was even or high, a response had to be given with the right hand. For some of the digits, the low/high and odd/even decisions required the same response hand (compatible digits), while for other digits, the response hand required for the low/high decisions differed from that required for the odd/even decisions (incompatible digits). For compatible digits, low/high decisions were performed faster and resulted in fewer errors than odd/even decisions. Incompatible digits resulted in longer reaction times and more errors, but only when an odd/even decision had to be made.

One possible interpretation for the interference of number magnitude on parity judgements is that magnitude is automatically extracted from numbers, becomes available before parity information, and interferes with the processing of other numerical properties (see also Dehaene and Akhavein, 1995). This interpretation raises the question how different properties of numbers, such as magnitude and parity, are processed and mentally represented. Current number processing models focus on the relationship between verbal and Arabic notation, the routes by which different types of input notation are transformed into a generic semantic representation, and the way in which semantic representations are used in mental arithmetic (e.g., Campbell and Clark, 1992; Dehaene, 1992; McCloskey, 1992). Little is known yet about the way in which *properties* of numbers are processed and represented. A critical question in this regard, is whether the interference of magnitude on parity judgements arises at the level of stimulus or response processing. If the interference effect arises at the level of response processing, then there would be no reason to think that magnitude and parity are represented in a different manner. The first aim of the present experiment, therefore, was to examine whether the interference from number magnitude on parity judgements arises at the level of stimulus or response processing.

Instead of assuming that magnitude and parity information are represented in a different manner, it is possible to explain the asymmetric interference effect in terms of the relative ease with which magnitude and parity information are used to prime the appropriate response. An advantage for magnitude information may arise because it is relayed to the response system more easily than parity information once it has become available. If two types of information have a different potential to prime their associated response, it would be expected that the more potent information interferes with the less potent information when they are mapped to different responses.

Consistent with this interpretation, Sudevan and Taylor observed a subtle variation in the amount of interference that was related to the position of a digit on the number line. It is known that low/high judgements are made faster when numbers are farther apart (both when a number has to be compared against an absolute reference value, and when two numbers have to be compared against each other; the so-called *distance effect*: Marcel and Forrin, 1974; Moyer and Landauer, 1967, Moyer and Landauer, 1973; Sekuler et al., 1971). If the interference depends on the relative ease with which magnitude information is used to prime its appropriate response, it would be expected that more interference occurs for digits that are at the extremes of the number line. This is indeed what was observed. The second aim of the present experiment was to examine the effects of distance from the low/high cut-point on the processing of magnitude and parity information.

Distance from a low/high cut-point is not the only factor that has been found to influence the ease with which magnitude information is extracted or used. For people who are used to a left-to-right writing system, magnitude information appears to be processed more easily when low numbers are mapped to the left side of space, and high numbers to the right side of space (Dehaene et al., 1990; Dehaene et al., 1993). Dehaene et al. (1993) asked subjects to decide whether a target number was odd or even. Responses to small numbers were faster when made with the left hand, while responses to large numbers were faster when made with the right hand. In a series of follow-up experiments, it was shown that it is not the particular response hand, but the particular side of space, that causes the interference of number magnitude on parity judgements. The association of low numbers with the left and large numbers with the right seemed to occur for subjects who are accustomed to a left-to-right writing culture (French subjects or Iranian subjects who have been in France for a long time). The association tended to be reversed for subjects who live in a right-to-left writing culture (Iranians).

The evidence for the influence of spatial response assignment implies that the mapping of low digit responses to the left hand and high digit responses to the right hand may capitalize on a natural tendency for the low/high dimension to be represented spatially as going from left to right. Such a tendency could be responsible for the magnitude advantage seen earlier (Sudevan and Taylor, 1987), because it would mean that the mapping of the magnitude property to a particular response would be implemented more easily when there is a natural relationship between stimuli and responses (see Kornblum et al., 1990, for a discussion of these issues). The third aim of the present experiment was to analyze the effect of the spatial response assignment of low/high judgements on the degree of interference of number magnitude on parity judgements. If interference of number magnitude on parity judgements is only observed when low numbers are mapped to the left, and high numbers to the right, side of space, then there is no reason to assume that magnitude information is *always* automatically extracted from numbers and will therefore interfere with the processing of other properties. This outcome would argue against the idea that magnitude and parity information are necessarily extracted at different rates, and represented in a different manner. Since spatial response assignment most plausibly has its effect at the response end of information processing, this outcome would also provide evidence that the interference effect as seen in the Sudevan and Taylor (1987) studies arises at the locus of response processing.

In summary, then, we had three goals with the present experiment: (i) to specify the locus in the information processing system of the interference of magnitude information on parity judgements; (ii) to examine the effects of distance from the low/high cut-point on the processing of magnitude and parity information; and (iii) to examine the effects of spatial response assignment of magnitude judgements on the interference of number magnitude on parity judgements.

The 'real-time' nature of event-related potentials (ERPs) enables a detailed study of the time course of information processing. ERPs are changes in the electrical activity of the brain over time, related to particular events like stimuli or responses. They are obtained from electrodes placed on the scalp and reflect the activity of a large number of synchronously activated neurons (see Coles et al., 1986; Coles and Rugg, 1995; and Donchin et al., 1978, for introductions to ERPs).

In the study to be described in this paper, we use two measures of the event-related brain potential, the *P300* and the *lateralized readiness potential.* We will employ the P300 component of the ERP as an index of the time required to evaluate a stimulus. The P300 is a positive-going component with a posterior scalp distribution, typically elicited between 300 and 900 ms after stimulus onset. It has consistently been found that manipulations of the duration of stimulus processing (such as stimulus discriminability or difficulty of categorization; Kutas et al., 1977) influence the latency of the P300. On the other hand, little or no effect on P300 latency is evident for manipulations of the duration of response processing (such as stimulus-response compatibility; Magliero et al., 1984). Hence, the latency of the P300 is thought to be related to the time required to evaluate a stimulus (for overviews of the arguments underlying this idea, see Donchin, 1981; and Donchin and Coles, 1988). When stimuli are more complex and require more time to evaluate, the P300 occurs later in time.

To measure response-related processing, we will employ the lateralized readiness potential (LRP; see De Jong et al., 1988; or Gratton et al., 1988). The LRP is related to the preparation for, and execution of, a motor response. When subjects prepare to move their hands, a negative potential occurs at the scalp, and the negativity is maximal at central sites contralateral to the responding hand. To estimate the degree to which the correct or incorrect response hand is preferentially activated, the difference between electrodes placed over left and right sides of the brain is computed. By averaging across left- and right-hand responses, possible lateralizations that are not related to the responding hand are eliminated. The resulting LRP waveform reflects the degree to which the correct or incorrect response is preferentially activated (see Coles, 1989).

Several other studies have used a psychophysiological approach to examine the locus of interference in so-called incompatible or incongruent conditions (for a review, see

Coles et al., 1995). For example, in the Eriksen flankers task (Eriksen and Eriksen, 1974), when target and noise letters call for different responses, reaction times are prolonged. In this case, ERP measures indicated that incompatibility influenced both stimulus- and response-related processes (Coles et al., 1985; Gratton et al., 1988; Smid et al., 1990). This and other examples of the success of ERPs in identifying the locus of interference suggested that a similar approach might be successful in the digit-judgement task.

Subjects performed a choice-reaction time task involving low/high and odd/even judgements about the digits 2 through 9 similar to that used by Sudevan and Taylor (1987). The digits were either close to, or far from, the low/high cut-point. The spatial response assignment for magnitude decisions was also varied. One group of subjects responded with the left hand to low digits and with the right hand to high digits. Another group of subjects responded with the left hand to high digits and with the right hand to low digits. The critical condition is when subjects must make a parity judgement about an incompatible digit, that is, a digit whose parity requires a response with one hand but whose magnitude requires a response with the other hand. If the interference in this condition arises at the level of the response system, the LRP should indicate that the incorrect hand is activated before the correct response is executed. If, in addition, the duration of stimulus processing is influenced, the P300 should occur later in time in this condition relative to the other conditions.

2. Method

2.1. Subjects

Eighteen paid volunteers between 20 and 42 years of age (ten female) were randomly assigned to one of two groups. All subjects had normal or corrected-to-normal visual acuity, and all but one male were right-handed, as assessed with the Edinburgh Handedness Inventory (Oldfield, 1971).

2.2. Stimuli and task

Subjects performed a choice-reaction time task involving magnitude and parity judgements about digits similar to that used by Sudevan and Taylor (1987). Each trial consisted of the presentation of a single digit (2, 3, 4, 5, 6, 7, 8, or 9), surrounded by letters indicating whether a magnitude or parity judgement had to be made about the digit. If the digit was surrounded by the letters ‘OD’ and ‘EV’, subjects had to decide if the digit was odd or even. If the digit was surrounded by the letters ‘LO’ and ‘HI’, subjects had to decide if the digit was low or high. Low digits were defined as 2, 3, 4, and 5; high digits as 6, 7, 8, and 9. Stimulus duration was 500 ms, with inter-stimulus intervals ranging between 2.9 and 3.5 s (in steps of 200 ms). Stimuli were approximately .5 degrees in height and 2.7 degrees in width. A plus sign served as fixation point. This was continuously present on the screen, except when a stimulus was presented. The fixation point occupied the same spatial location as the digit in a stimulus array.

The two groups of subjects received different spatial response assignments for magnitude judgements. In the 'low-left, high-right' group, subjects had to respond with the left hand to low digits and with the right hand to high digits. Here, digits were surrounded by the letters 'LO' to the left and 'HI' to the right to denote the low/high judgement, and 'OD' to the left and 'EV' to the right to denote the odd/even judgement. If the digit was odd or low, subjects were required to respond by squeezing a zero-displacement dynamometer with the left hand; if the digit was even or high, a dynamometer had to be squeezed with the right hand (see Kutas and Donchin, 1980). In the 'high-left, low-right' group, subjects had to respond with the left hand to high digits and with the right hand to low digits. The digits were now surrounded by the letters 'HI' to the left and 'LO' to the right to denote the low/high judgement, and 'OD' to the left and 'EV' to the right to denote the odd/even judgement. If the digit was odd or high, subjects were required to squeeze a zero-displacement dynamometer with the left hand; if the digit was even or low, a dynamometer had to be squeezed with the right hand. Note that the position of the letters designating the low/high judgement on the screen was kept congruent with the spatial response assignment. The two dynamometers (Sensotec, Inc.) were placed on a table in front of the subjects.

The important feature of this task is that for some digits, the low/high and odd/even judgements required the same response hand (*compatible* digits), while for other digits, the response hand required for the low/high judgement differed from that required for the odd/even judgement (*incompatible* digits). For the 'low-left, high-right' group, compatible digits were 3, 5, 6, and 8, and incompatible digits 2, 4, 7, and 9. For the 'high-left, low-right' group, compatible digits were 2, 4, 7, and 9, and incompatible digits 3, 5, 6, and 8. Note that across the two groups, the actual digits comprising the compatible and incompatible digits reversed.

2.3. Procedure

The experiment consisted of two sessions of about three hours each, carried out on consecutive days. Subjects were seated in a sound-isolated room facing a computer monitor at a distance of 1 m. On the first day, subjects were given an explanation about the task with instructions that stressed speed more than accuracy. This was followed by an explanation about how responses should be given with the dynamometers. Response criteria were then established for each hand separately. Subjects were required to squeeze each dynamometer as hard as they could, separately with their left and with their right hand. Then, criterion levels were established representing 25% of the maximum force level of the left hand, and 25% of the maximum force level of the right hand. These force levels served as the criterion for a complete response, that is, when the subject squeezed with a force level that exceeded the criterion, a response was registered.

On each day, subjects started with a block of 112 practice trials, and auditory feedback (a tone of approximately 800 Hz and 60 dB SPL) was given during the interval in which the force of the response exceeded the criterion. Then, ten blocks of 112 experimental trials each were administered. No feedback was given during these trials. The 112 trials in a block were randomized in groups of 16. In each group of 16 trials, each of the 16 event types (low/high and odd/even judgements about each of the 8 digits) was randomly assigned once. Thus, within a block of 112 trials, there were 7 instances of each of the 16 event types. Across the whole experiment, each of the 16 event types occurred 140 times. Subjects rested for a few minutes between each block and could rest as long as they wanted in the middle of an experimental session.

2.4. Psychophysiological recording

The electroencephalogram (EEG) was recorded using silver/silver-chloride electrodes from Fz, Cz, Pz (according to the 10/20 international system, Jasper, 1958), from sites 4 cm to the left (C3′) and to the right (C4′) of Cz, and from the right mastoid. All electrodes were referred to the left mastoid. The vertical EOG was recorded from electrodes placed above and below the right eye and the horizontal EOG was recorded from electrodes placed near the outer canthus of each eye. An electrode placed 2 cm above the nose bridge served as ground. Electrodes were attached between the block of practice trials and the experimental trials.

The EEG and EOG signals were amplified with Grass amplifiers (Neurodata model 12) and bandpass filtered (−3dB roll-off) with half-amplitude frequencies of 0.01 and 30 Hz. All signals were digitized at a rate of 200 Hz and the digital data were stored on optical disk for off-line analyses.

2.5. Data analysis

The reaction time measures were based on the time at which the force exerted on the dynamometers exceeded the criterion. The EEG was algebraically re-referenced to linked mastoids (that is, for each data point, half of the activity recorded from the right mastoid was subtracted from the other electrode sites). For each single trial, the EEG was corrected for eye movement artifacts using the procedure described in Gratton et al. (1983) and extended by Miller et al. (1988).

Average ERP waveforms were computed for each electrode site for the sixteen events defined by type of judgement (low/high or odd/even judgement) and digit (2, 3, 4, 5, 6, 7, 8, or 9). Trials for which an incorrect response was given or for which the limits of the analog-to-digital converter were reached were excluded from the average waveforms. ERP waveforms were low-pass filtered at 6 Hz (half amplitude) with the digital filter described in Cook and Miller (1992).

Lateralized readiness potential waveforms were computed with the formula given in Coles (1989):

$$\mathrm{LRP} = \left[\mathrm{Mean}(C4' - C3')_{\text{left-hand movement}} + \mathrm{Mean}(C3' - C4')_{\text{right-hand movement}}\right]/2.$$

In words, the voltage at C3′ was subtracted from that at C4′ for trials when the left hand response was correct, the voltage at C4′ was subtracted from that at C3′ for trials when the right hand response was correct, and an unweighted average of these difference waveforms was then created. With this method, a negative value indicates that the correct response hand was activated, while a positive value indicates that the incorrect response hand was activated.

Initially, the 16 event types were combined into *compatible low/high judgements*, *compatible odd/even judgements*, *incompatible low/high judgements*, and *incompatible odd/even judgements*. In a second step in the analysis, the data were divided as a function of the position that the digit occupied on the number line (that is, as a function of the distance of the digit from the low/high cut-point). Average waveforms were computed for *extreme compatible low/high judgements*, *nonextreme compatible low/high judgements*, *extreme compatible odd/even judgements*, *nonextreme compatible odd/even judgements*, *extreme incompatible low/high judgements*, *nonextreme incompatible low/high judgements*, *extreme incompatible odd/even judgements*, and *nonextreme incompatible odd/even judgements*.

Unless otherwise specified, the data were statistically evaluated with repeated measures analyses of variance (ANOVA), incorporating the Greenhouse-Geisser correction (Keselman and Rogan, 1980) when appropriate. Tukey's Honestly Significant Difference tests were used to test for the reliability of post-hoc comparisons.

3. Results

3.1. Overt responses

The effects of type of judgement, compatibility, and spatial response assignment on mean reaction times and proportions of incorrect responses are shown in Fig. 1 and Fig. 2, respectively. There were no reliable overall speed or accuracy differences across the two spatial response assignment groups, nor was there an interaction with type of judgement. The mean reaction times showed a reliable interaction between spatial response assignment group, compatibility, and type of judgement ($F(1,16) = 11.78$, $p = 0.003$). For the 'low-left, high-right' group, incompatible digits resulted in longer reaction times, but only when an odd/even decision had to be made. For the 'high-left, low-right' group, by contrast, incompatible digits resulted in longer reaction times regardless of the type of judgement that had to be made. The proportions of incorrect responses essentially followed the same pattern, although the interaction between compatibility and type of judgement ($F(1,16) = 10.67$, $p = 0.005$) was not reliably different across spatial response assignment groups. Thus, the asymmetric interference effect of number magnitude on parity judgements as observed earlier by Sudevan and Taylor (1987) was replicated. However, this asymmetric effect was only observed when low numbers were associated with the left response and high numbers with the right response. With the reversed response assignment, a symmetric interference effect between number magnitude and parity resulted.

To examine the influence of distance from the low/high cut-point, the data were divided as a function of the position of each digit on the number line. Fig. 1 and Fig. 2 also show the data separately for digits that were far from the low/high cut-point (extreme digits) and for digits that were close to the low/high cut-point (nonextreme digits). In the 'low-left, high-right' group, the asymmetric interference effect of number magnitude on parity judgements appears larger for digits that were at the extreme ends of the number line. The difference between extreme and nonextreme digits results

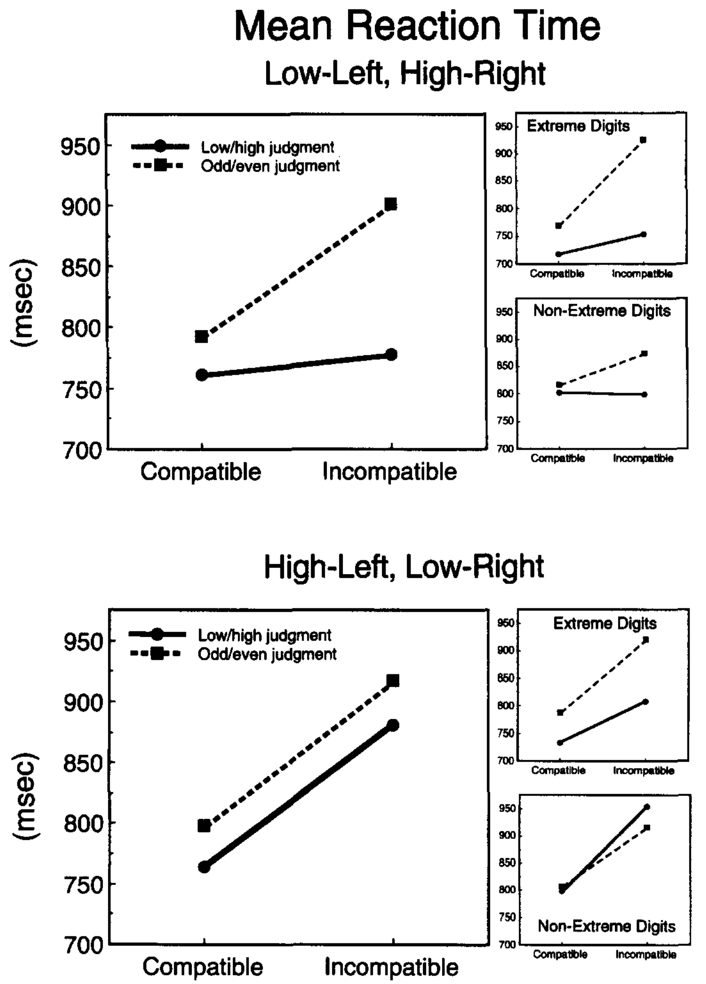

Fig. 1. Mean reaction times (in ms) as a function of type of judgement and compatibility. The data are shown separately for the 'low-left, high-right' and 'high-left, low-right' groups. Also shown are the data for digits that were farther from the low/high cut-point (extreme digits) and those for digits that were closer to the low/high cut-point (nonextreme digits).

primarily from the condition in which odd/even judgements have to be made about incompatible digits. Incompatible odd/even judgements take longer, and result in more incorrect responses, for extreme than nonextreme digits. In the 'high-left, low-right' group, the symmetric interference effect between number magnitude and parity appears to be present primarily for digits that were at the nonextreme ends of the number line. For extreme digits, a slight asymmetry in the interference can be seen. The difference between extreme and nonextreme digits in this group results primarily from the condition in which low/high judgements have to be made about incompatible digits. Incompatible low/high judgements take longer, and are less accurate, for nonextreme

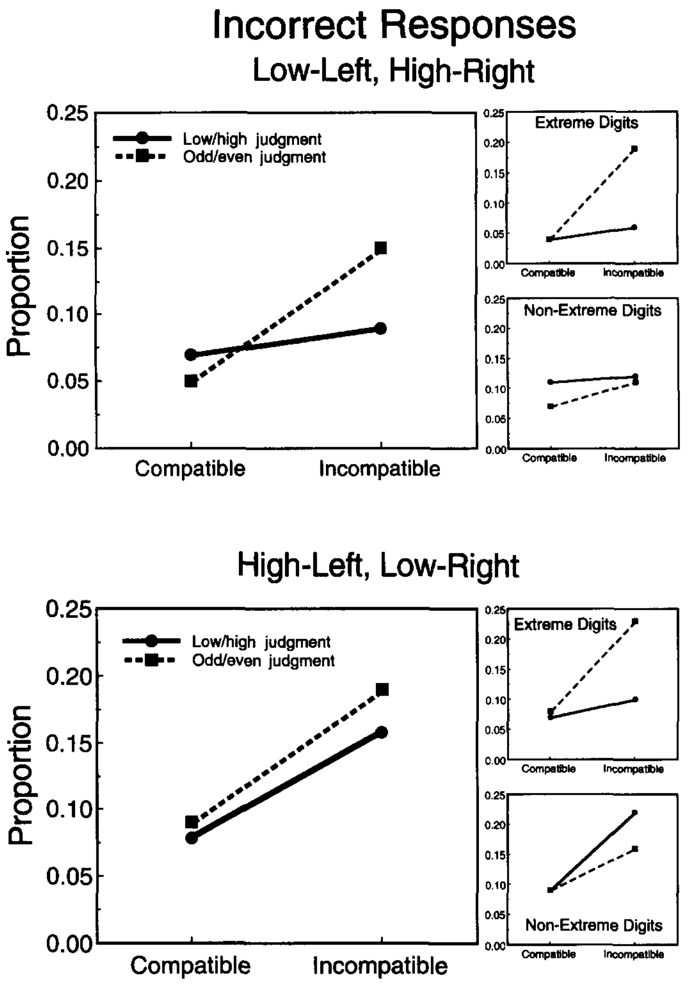

Fig. 2. Proportions of incorrect responses as a function of type of judgement and compatibility. The data are shown separately for the 'low-left, high-right' and 'high-left, low-right' groups. Also shown are the data for digits that were farther from the low-high cut-point (extreme digits) and those for digits that were closer to the low-high cut-point (nonextreme digits).

than extreme digits. Statistically, the interaction between compatibility, type of judgement, and extremity reached significance (mean reaction time: $F(1,16) = 18.78$, $p < 0.001$ and proportion of incorrect responses: $F(1,16) = 19.21$, $p < 0.001$), but the interaction with spatial response assignment group was not reliable.

In summary, when low numbers were assigned to the left response and high numbers to the right response, information about the magnitude of a digit interfered with the decision about the parity of the digit. This interference was larger for numbers that were far away from the low/high cut-point. When low numbers were assigned to the right response and high numbers to the left response, a symmetric interference between magnitude and parity information was observed. Information about the magnitude of a digit interfered with the decision about the parity of the digit, and information about the parity of a digit interfered with the decision about the magnitude of the digit. The symmetric interference was most pronounced for digits that were close to the low/high cut-point. For digits that were far from the cut-point, magnitude information interfered more with parity information than vice versa.

3.2. *Event-related potentials*

3.2.1. *P300*

The grand average ERP waveforms associated with low/high and odd/even judgements about compatible and incompatible digits are shown in Fig. 3. The waveforms are characterized by a positive peak between 300 and 800 ms after stimulus presentation, with a scalp distribution that conforms to the distribution of the P300. The amplitude of this positivity is largest at the posterior electrode and decreases rapidly from the back to the front of the head. The P300 was quantified in the individual subjects' averages as the maximum peak between 300 and 800 ms post-stimulus at the Pz electrode, relative to the 100 ms pre-stimulus baseline. A clear peak could be observed in all subjects and conditions. The latency of the P300 was defined as the time at which the maximum peak occurred.

Fig. 4 presents the ERP waveforms for the Pz electrode to allow a comparison of the effects of type of judgement and compatibility on the P300 (waveforms for extreme and nonextreme digits are also shown). As can be seen, the latency of the P300 does not appear to change across conditions. The only effect on P300 latency that reached statistical significance was the interaction between type of judgement, extremity, and response assignment group ($F(1,16) = 7.18$, $p = 0.017$). In the 'high-left, low-right' group, low/high judgements about extreme digits elicited a P300 with a longer latency than low/high judgements about nonextreme digits, whereas the reverse was true for odd/even judgements. However, although the interaction was significant, none of these comparisons were individually significant. For P300 amplitude, there was an interaction between compatibility and response assignment group ($F(1,16) = 6.58$, $p = 0.021$). P300 amplitude was smaller for incompatible than compatible digits in the 'high-left, low-right' group, whereas no reliable effects emerged in the 'low-left, high-right' group.

In short, the time of occurrence of the P300 did not change across experimental conditions in either response assignment group. P300 amplitude, however, was smaller for incompatible than compatible digits when high numbers were associated with the left response, and low numbers with the right response.

3.2.2. *Lateralized readiness potential*

The grand average LRP waveforms are depicted in Fig. 5. Odd/even judgements about incompatible digits in the 'low-left, high-right' group were associated with an initial activation of the incorrect response hand, an effect that seems larger for digits at the extremes of the number line. No incorrect response activation is apparent in any of the conditions in the 'high-left, low-right' group.

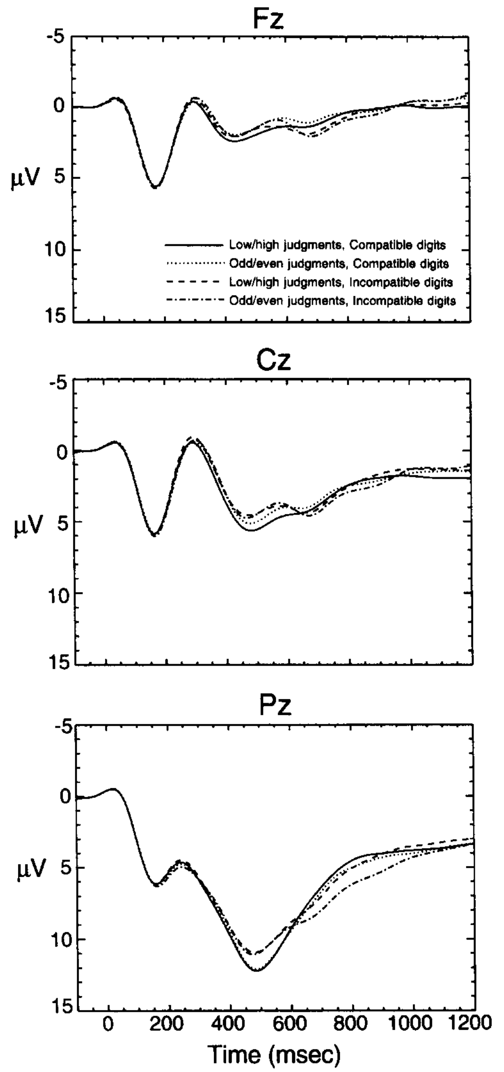

Fig. 3. Grand average ERP waveforms for the Fz, Cz, and Pz electrode sites, associated with low/high and odd/even judgements about compatible and incompatible digits.

The reliability of the incorrect response activation was evaluated in each condition with t-tests (against the null hypothesis of zero) on consecutive time points of the appropriate LRP waveforms. Because such tests are not mutually independent and because of the number of tests we performed, an incorrect response activation was considered significant only when at least 5 consecutive tests achieved significance at $p < 0.05$ with the difference in each case reflecting the same polarity. The incorrect

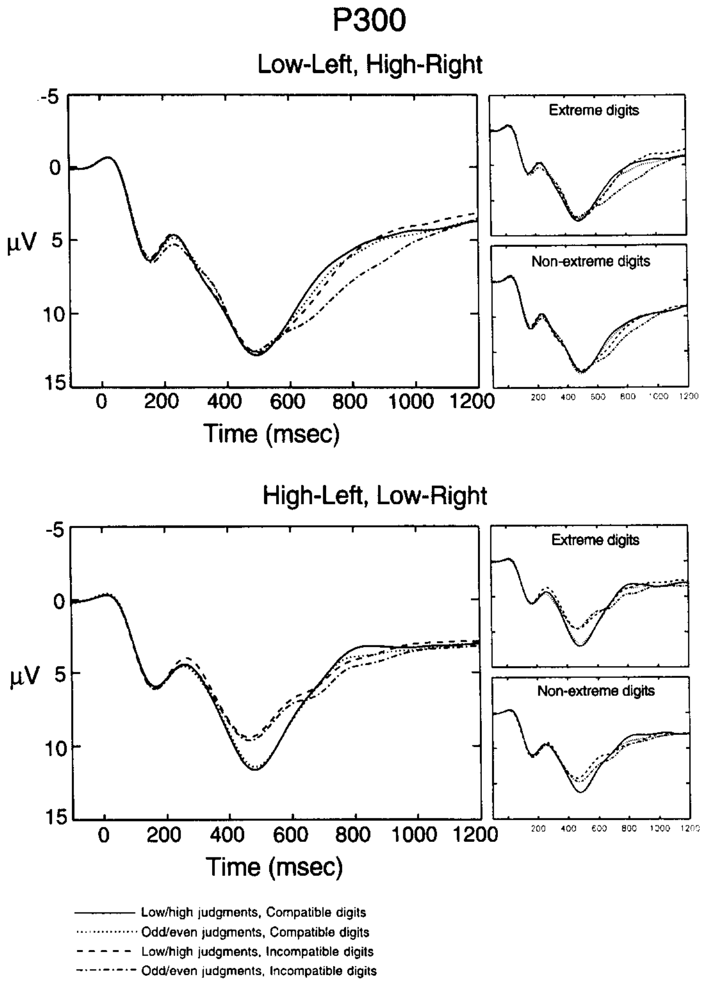

Fig. 4. Grand average ERP waveforms for the Pz electrode as a function of type of judgement and compatibility, for the 'low-left, high-right' and 'high-left, low-right' groups separately. The data for digits that were farther from the low-high cut-point (extreme digits) and those for digits that were closer to the low-high cut-point (nonextreme digits) are also shown separately.

response activation seen for incompatible odd/even judgements in the 'low-left, high-right' group was reliably different from zero between 210 and 340 ms after stimulus onset ($t(8)$ between 2.34 and 4.97, all $p < 0.05$). None of the other experimental conditions was associated with a reliable incorrect response activation. Consecutive t-tests on the difference between extreme and nonextreme digits did not suggest that the larger incorrect response activation seen for extreme digits was reliable at any time point. A direct comparison between groups indicated that the LRP for incompatible odd/even decisions differed reliably across the two response assignment groups be-

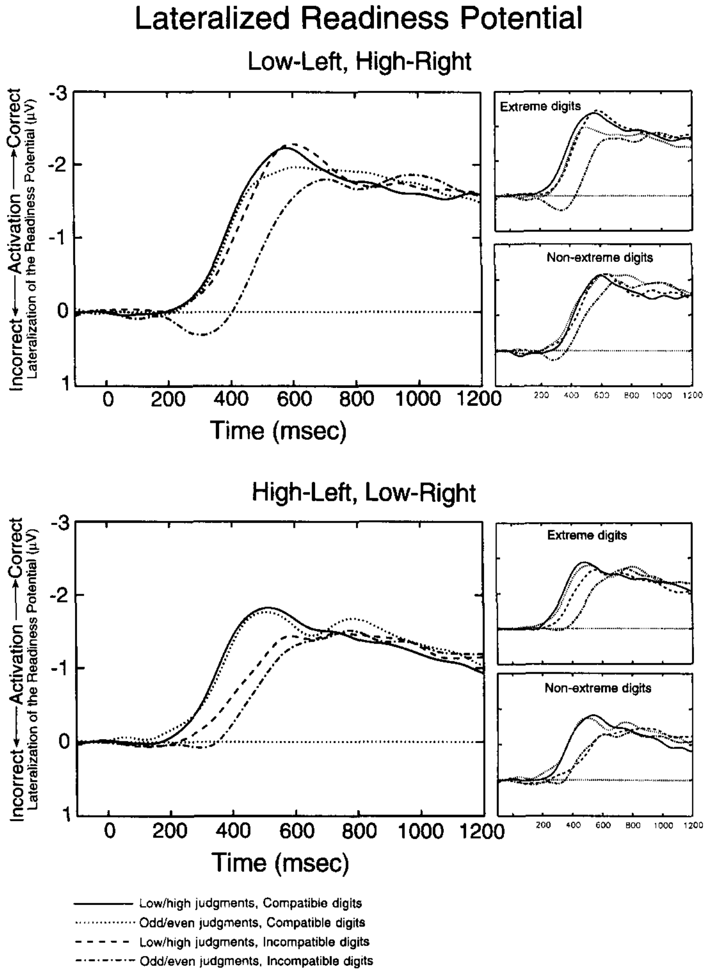

Fig. 5. Grand average LRP waveforms as a function of type of judgement and compatibility, for the 'low-left, high-right' and 'high-left, low-right' groups separately. The data for digits that were farther from the low-high cut-point (extreme digits) and those for digits that were closer to the low-high cut-point (nonextreme digits) are also shown separately.

tween 240 and 300 ms after stimulus onset (point-by-point t-tests: $t(16)$ between 2.18 and 2.70, all $p < 0.05$).

4. Discussion

The present data replicate earlier findings that when subjects make 'odd/even' and 'low/high' decisions about digits, information about the digit's magnitude can interfere with the decision about the digit's parity (Sudevan and Taylor, 1987). Subjects viewed single digits, surrounded by letters indicating whether a magnitude or parity judgement had to be made. Some of these digits required the same response hand for the magnitude and parity decisions (*compatible* digits), while other digits required a different response hand for the magnitude and parity decisions (*incompatible* digits). The results showed that when low numbers were associated with the left response and high numbers with the right response, incompatible digits gave rise to longer reaction times and more incorrect responses only when an odd/even judgement had to be made.

The interference of number magnitude on parity judgements suggests that magnitude information is obtained, or used, more readily than parity information. The current experiment served three aims, all intended to obtain a better understanding of how properties of numbers are processed and mentally represented. First, we wanted to specify the locus in the information processing system at which the interference of magnitude information on parity judgements arises. Is magnitude information obtained more readily from numbers than parity information? Or, are magnitude and parity information obtained in parallel, but magnitude information is used more readily for subsequent (response) processing? Second, we wanted to examine the effect of distance from the low/high cut-point on the processing of magnitude and parity information. Third, we wanted to examine the effect of a reversal of the spatial response assignment of magnitude judgements on the processing of magnitude and parity information.

4.1. The locus of interference between magnitude and parity information

If the interference in the digit-judgement task arises at the level of the response system, the LRP should indicate that the incorrect response is activated before the correct response is executed, with no increase in P300 latency. If, in addition, stimulus-related processes are prolonged, then an increase in P300 latency would be evident.

The LRP data showed that incompatible odd/even decisions were associated with an initial incorrect response activation when low numbers were associated with the left, and high numbers with the right, response. No differences in P300 latency emerged across experimental conditions. [2] Since P300 latency is thought to be correlated with the time required for stimulus evaluation, magnitude information was on this account not evaluated more easily than parity information. Therefore, the data point to a response locus for the asymmetric interference effect of magnitude information on parity judgements. When a parity judgement has to be made about a digit whose parity and magnitude require responses with different hands, the magnitude of the digit initially activates the incorrect response hand, which then competes with the correct response. This view is consistent with the idea that, when a stimulus possesses multiple properties that call for conflicting responses, interference effects typically arise at the level of response processing (Kornblum et al., 1990).

[2] In a separate experiment, we replicated the observation of incorrect response activation for incompatible odd/even decisions when low numbers were assigned to the left hand and high numbers to the right hand. Differences in the latency of the P300 were again not observed.

4.2. Distance from low / high cut-point

The degree of interference between magnitude and parity information was influenced by the distance of a digit to the low/high cut-point. With the left-to-right response assignment, the asymmetric interference from magnitude information on parity judgements increased as the distance between a digit and the low/high cut-point increased. To explain this distance effect, it is reasonable to assume that information about the magnitude of digits that are far from a reference point is more distinct than information about the magnitude of digits that are close to a reference point. On the other hand, information about the parity of digits is presumably not influenced by the distance of the digit to a reference point. Therefore, magnitude information is capable of interfering consistently with the parity judgement, whereas the reverse could not occur.

There is some evidence that the distance effect is due to the distance between the number and its reference point (Holyoak, 1978). However, an interpretation of the distance effect in terms of the distance between the number and the extremes of the number line is possible, as our experiment did not include a direct test to dissociate these two interpretations. It is important to note that either interpretation would lead to similar conclusions about the major questions that motivated this study.

The psychophysiological data suggest that just as with the interference between magnitude and parity information, the distance effect exerts its influence at the response end of information processing. The incorrect response activation in the LRP was larger for digits that were farther from the reference point (although this effect was not reliable), whereas no differences in P300 latency or amplitude were observed.

4.3. Spatial response assignment of magnitude judgements

Based on arguments presented above, it appears that with a left-to-right response assignment, magnitude and parity information are extracted in the same fashion under all conditions. The amount of interference from one type of information on another depends on the association between the information and the response (cf. Cohen et al., 1990; Logan, 1980). A question of interest is whether the amount of interference from one type of information on another also depends on the spatial response assignment of magnitude judgements. A left-to-right response assignment capitalizes on a natural tendency for magnitude information to be represented in a left-to-right manner, and may mask the way in which magnitude information is processed under other circumstances.

When the spatial response assignment for magnitude judgements was reversed, a *symmetric* interference effect between number magnitude and parity was seen. Thus, it appears that, when low numbers were mapped to the right response and high numbers to the left response, neither magnitude nor parity information had an advantage over the other type of information. On some trials, magnitude information became available before parity information, while on others, the reverse occurred. Thus, information about magnitude could interfere with the decision as to whether a digit was odd or even, but the opposite could also occur.

The symmetric interference effect was most pronounced for digits that were close to the low/high cut-point. For digits that were far from the cut-point, magnitude information interfered more with parity judgements than vice versa. Therefore, even when low numbers are assigned to the right hand, and high numbers to the left hand, magnitude information about extreme digits seems distinct enough to be capable of interfering consistently with the parity judgement.

The symmetry in the interference between magnitude and parity information in the 'high-left, low-right' group resulted from an increase in reaction times for incompatible low/high decisions relative to compatible low/high decisions. There are two possible explanations for this increase. First, the increase could be a true consequence of the reversal of the response assignment. Second, it is possible that the increase is a byproduct of the change in relative positions that the incompatible digits occupied on the number line in each group. An unavoidable consequence of reversing the response assignment was that the actual digits that comprised the compatible and incompatible digit sets changed across response assignments. In the 'high-left, low-right' group, incompatible digits were on the average closer to the low/high cut-point. Because of the distance effect, low/high decisions could be expected to take longer in the 'high-left, low-right' group for this reason.

The question of the importance of proximity to the cut-point can be addressed by comparing the results for nonextreme digits in the 'low-left, high-right' group with those for extreme digits in the 'high-left, low-right' group. The nonextreme incompatible digits in the 'low-left, high-right' group are closer to the low/high cut-point than the extreme incompatible digits in the 'high-left, low-right' group. If the interference effect observed for extreme incompatible low/high judgements is a result of the closer proximity to the cut-point, then a similar or larger interference effect should have been present for incompatible nonextreme low/high judgements in the 'low-left, high-right' group. For these digits, however, incompatible low/high judgements did not give rise to longer reaction times. Thus, the most parsimonious explanation for the symmetric interference effect observed when low numbers are associated with the right hand and high numbers with the left hand, is the reversal of the low/high response assignment.

Although the reaction time and accuracy measures showed an interference effect from magnitude information on parity judgements and vice versa, this interference was not reflected in a P300 latency difference or an incorrect response activation in the LRP. The question therefore arises what the source of the interference is when neither the P300 nor the LRP show an effect. One possible explanation is that an incorrect response activation in the LRP will only be observed when one type of information has a much stronger association with the response than another. It could be expected that neither type of information 'wins the race for the response' when both types of information are equally strongly associated with the response (cf. Townsend and Ashby, 1983). Furthermore, it should be noted that even though P300 latency did not change across conditions, the P300s associated with incompatible digits in the right-to-left response assignment group were of smaller amplitude than those associated with the other conditions. Some evidence of the interference effect was thus reflected in the psychophysiological measures. At present, we do not have an interpretation for the differences in P300 amplitude. Although the evidence for using P300 latency as an index of stimulus evaluation time is strong, many different interpretations have been offered for P300 amplitude differences, none of which seems applicable in the current situation.

5. Conclusion

Taken together, the pattern of results obtained in the present experiment can be explained by proposing that magnitude and parity information are extracted in the same fashion in all conditions. The amount of interference depends on the association between the information and the response (cf. Cohen et al., 1990; Logan, 1980). This, in turn, depends on the naturalness of the spatial response assignment and the distance from the low/high cut-point. The farther a digit is from the low/high cut-point, the stronger the association between magnitude information and its response, and the more interference will be seen from magnitude information. With the natural 'low-left, high-right' assignment, there is a strong association between magnitude information and its corresponding response, thereby causing interference with the slower parity response. With the less natural 'high-left, low-right' assignment, the associations between magnitude and parity information and their corresponding responses are of about equal strength. The magnitude response will be primed more slowly than in the 'low-left, high-right' group and, as a result, its potential interference with the parity response is reduced. We therefore suggest that future research, aimed at understanding how properties of numbers are processed, focus on the relationship between numerical properties and the required response(s).

Acknowledgements

This research was supported by grant MH41445 from the National Institutes of Mental Health.

References

Campbell, J.I.D. and J.M. Clark, 1992. 'Cognitive number processing: An encoding-complex perspective'. In: J.I.D. Campbell (Ed.), The nature and origins of mathematical skills (pp. 457–491). Amsterdam: North-Holland.

Cohen, J.D., K. Dunbar and J.L. McClelland, 1990. On the control of automatic processes: A parallel distributed processing account of the Stroop effect. Psychological Review 97, 332–361.

Coles, M.G.H., 1989. Modern mind–brain reading: Psychophysiology, physiology, and cognition. Psychophysiology 26, 251–269.

Coles, M.G.H., G. Gratton, T.R. Bashore, C.W. Eriksen and E. Donchin, 1985. A psychophysiological investigation of the continuous flow model of human information processing. Journal of Experimental Psychology: Human Perception and Performance 11, 529–553.

Coles, M.G.H., G. Gratton, A.F. Kramer and G.A. Miller, 1986. 'Principles of signal acquisition and analysis'. In: M.G.H. Coles, E. Donchin and S.W. Porges (Eds.), Psychophysiology: Systems, processes and applications (pp. 183–221). New York: The Guilford Press.

Coles, M.G.H. and M.D. Rugg, 1995. 'Event-related brain potentials: An introduction'. In: M.D. Rugg and M.G.H. Coles (Eds.), Electrophysiology of mind: Event-related brain potentials and cognition (pp. 1–26). New York: Oxford University Press.

Coles, M.G.H., H.G.O.M. Smid, M.K. Scheffers and L.J. Otten, 1995. 'Mental chronometry and the study of human information processing'. In: M.D. Rugg and M.G.H. Coles (Eds.), Electrophysiology of mind: Event-related brain potentials and cognition (pp. 86–131). New York: Oxford University Press.

Cook, E.W. and G.A. Miller, 1992. Digital filtering: Background and tutorial for psychophysiologists. Psychophysiology 29, 350–367.

Dehaene, S., 1992. Varieties of numerical abilities. Cognition 44, 1–42.

Dehaene, S. and R. Akhavein, 1995. Attention, automaticity, and levels of representation in number processing. Journal of Experimental Psychology: Learning, Memory, and Cognition 21, 314–326.

Dehaene, S., S. Bossini and P. Giraux, 1993. The mental representation of parity and number magnitude. Journal of Experimental Psychology: General 122, 371–396.

Dehaene, S., E. Dupoux and J. Mehler, 1990. Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. Journal of Experimental Psychology: Human Perception and Performance 16, 626–641.

De Jong, R., M. Wierda, G. Mulder and L.J.M. Mulder, 1988. Use of partial information in responding. Journal of Experimental Psychology: Human Perception and Performance 14, 682–692.

Donchin, E., 1981. Surprise! ... Surprise? Psychophysiology 18, 493–513.

Donchin, E. and M.G.H. Coles, 1988. Is the P300 component a manifestation of context updating? Behavioral and Brain Sciences 11, 355–425.

Donchin, E., W. Ritter and W.C. McCallum, 1978. 'Cognitive psychophysiology: The endogenous components of the ERP'. In: E. Callaway, P. Tueting and S.H. Koslow (Eds.), Event-related brain potentials in man (pp. 349–411). New York: Academic Press.

Eriksen, B.A. and C.W. Eriksen, 1974. Effects of noise letters upon the identification of a target letter in a nonsearch task. Perception and Psychophysics 16, 143–149.

Gratton, G., M.G.H. Coles and E. Donchin, 1983. A new method for off-line removal of ocular artefact. Electroencephalography and Clinical Neurophysiology 55, 468–484.

Gratton, G., M.G.H. Coles, E. Sirevaag, C.W. Eriksen and E. Donchin, 1988. Pre- and post-stimulus activation of response channels: A psychophysiological analysis. Journal of Experimental Psychology: Human Perception and Performance 14, 331–344.

Henik, A. and J. Tzelgov, 1982. Is three greater than five: The relation between physical and semantic size in comparison tasks. Memory and Cognition 10, 389–395.

Holyoak, K.J., 1978. Comparative judgments with numerical reference points. Cognitive Psychology 10, 203–243.

Jasper, H.H., 1958. The ten–twenty electrode system of the International Federation. Electroencephalography and Clinical Neurophysiology 10, 371–375.

Keselman, H.J. and J.C. Rogan, 1980. Repeated measures *F* tests and psychophysiological research: Controlling the number of false positives. Psychophysiology 17, 499–503.

Kornblum, S., T. Hasbroucq and A. Osman, 1990. Dimensional overlap: Cognitive basis for stimulus-response compatibility – A model and taxonomy. Psychological Review 97, 253–270.

Kutas, M. and E. Donchin, 1980. Preparation to respond as manifested by movement-related brain potentials. Brain Research 202, 95–115.

Kutas, M., G. McCarthy and E. Donchin, 1977. Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. Science 197, 792–795.

Logan, G.D., 1980. Attention and automaticity in Stroop and priming tasks: Theory and data. Cognitive Psychology 12, 523–553.

Magliero, A., T.R. Bashore, M.G.H. Coles and E. Donchin, 1984. On the dependence of P300 latency on stimulus evaluation processes. Psychophysiology 21, 171–186.

Marcel, T. and B. Forrin, 1974. Naming latency and the repetition of stimulus categories. Journal of Experimental Psychology 103, 450–460.

McCloskey, M., 1992. Cognitive mechanisms in numerical processing: Evidence from acquired dyscalculia. Cognition 44, 107–157.

Miller, G.A., G. Gratton and C.M. Yee, 1988. Generalized implementation of an eye-movement correction procedure. Psychophysiology 25, 241–243.

Moyer, R.S. and T.K. Landauer, 1967. Time required for judgements of numerical inequality. Nature 215, 1519–1520.

Moyer, R.S. and T.K. Landauer, 1973. Determinants of reaction time for digit inequality judgments. Bulletin of the Psychonomic Society 1, 167–168.

Oldfield, R.C., 1971. The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia 9, 97–113.

Sekuler, R., E. Rubin and R. Armstrong, 1971. Processing numerical information: A choice time analysis. Journal of Experimental Psychology 90, 75–80.

Smid, H.G.O.M., G. Mulder and L.J.M. Mulder, 1990. Selective response activation can begin before stimulus recognition is complete: A psychophysiological and error analysis of continuous flow. Acta Psychologica 74, 169–201.

Sudevan, P. and D.A. Taylor, 1987. The cuing and priming of cognitive operations. Journal of Experimental Psychology: Human Perception and Performance 13, 89–103.

Townsend, J.T. and F.G. Ashby, 1983. Stochastic modeling of elementary psychological processes. Cambridge: Cambridge University Press.

Tzelgov, J., J. Meyer and A. Henik, 1992. Automatic and intentional processing of numerical information. Journal of Experimental Psychology: Learning, Memory and Cognition 18, 166–179.