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On the Transmission of Partial Information: Inferences From Movement-Related Brain Potentials

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Results are reported from a new paradigm that uses movement-related brain potentials to detect response preparation based on partial information. The paradigm uses a hybrid choice-reaction go/nogo procedure in which decisions about response hand and whether to respond are based on separate stimulus attributes. A lateral asymmetry in the movement-related brain potential was found on nogo trials without overt movement. The direction of this asymmetry depended primarily on the signaled response hand rather than on properties of the stimulus. When the asymmetry first appeared was influenced by the time required to select the signaled hand, and when it began to differ on go and nogo trials was influenced by the time to decide whether to respond. These findings indicate that both stimulus attributes were processed in parallel and that the asymmetry reflected preparation of the response hand that began before the go/nogo decision was completed.

Recently there has been renewed interest in an integration of cognitive psychology and the neurosciences. The chronometric study of human information processing is one area that has benefitted from these developments. A promising consequence has been the increased use of psychophysiological measures to draw inferences about the temporal properties of cognitive processes (Coles, 1989; Meyer, Osman, Irwin, & Yantis, 1988; van der Molen, Bashore, Halliday, & Callaway, 1991). The present study represents a further example of this emerging synthesis between mental chronometry and psychophysiology.

We address an issue that is especially important for the chronometric study of information processing but that has been difficult to investigate with behavioral measures alone. This issue concerns the transmission of *partial information*. Partial information refers to the preliminary results of a process that are transmitted to subsequent contingent processes. For example, in a choice reaction time task, the transmission of partial information from perceptual to response processes may enable response selection or preparation to begin before the stimulus has been identified completely.

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The concept partial-information transmission may be better understood by considering several alternative models used to interpret reaction times. Such models involve a chain of contingent processes, in which each process operates on the output of its predecessor. In a strict serial stage model (Sternberg, 1969) there is no partial-information transmission. Rather, on completion, each component process passes the results of its computations to the next in a single quantum of information. In a cascade model (McClelland, 1979), each process continuously transmits partial information to its successor. This allows temporal overlap between contingent processes, because each one has input before its predecessor has completed its computations. It is also possible to have hybrid models involving both types of information transmission (Miller, 1988a). In such models, the all-or-none transmission of information divides the entire chain of processes into two or more serial stages, and the transmission of partial information allows for the temporal overlap of the processes within each serial stage.

From these models, it can be seen that the transmission of partial information delimits the extent and boundaries of serial stages: Partial-information transmission can only occur between processes within the same serial stage, and the existence of two or more serial stages requires that there be all-or-none transmission between one or more pairs of processes. Because of its intimate connection with the definition of a serial stage, the transmission of partial information also has implications for the interpretation of reaction times. For example, the assumption that reaction times can be decomposed into serial stages is necessary for the method of subtraction (Donders, 1868/1969) and provided the foundation for the method of additive factors (Sanders, 1980; Sternberg, 1969; but see McClelland, 1979). Attempts to strengthen further the interpretation of reaction times have therefore led to studies designed to detect the transmission of partial information and discover the conditions under which it arises (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Meyer, Irwin, Osman, & Kounios, 1988; Meyer, Yantis, Osman, & Smith, 1985; Miller, 1982, 1983, 1987).

Measurements of partial information may also provide insights concerning the individual process by which it was generated. The existence and content of partial-information transmission may provide important clues concerning the mechanism by which a process operates and the representation that it operates on. For example, some models of mental rotation posit continuous transformation of analog representations (e.g., Shepard & Metzler, 1971), whereas others posit computations based on a propositional representation (e.g., Just & Carpenter, 1976). One might expect partial information concerning intermediate rotations in the former case but not the latter. Such considerations have prompted measurements of the partial information transmitted by a number of processes, including those involved in visual perception (e.g., Coles et al., 1985; de Jong, Wierda, Mulder, & Mulder, 1988; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Miller, 1982, 1983, 1987; Smid, Mulder, & Mulder, 1990), mental imagery (Goldberg, 1985), word recognition (Meyer, Yantis, et al., 1985; Ratcliff, 1988; Yantis & Meyer, 1988), and retrieval of information from semantic memory (Kounios, Osman, & Meyer, 1987).

Experimental paradigms used to measure the transmission of partial information have tended to fall into two classes. One class involves the analysis of errors under conditions in which processing time is limited. Such limitations have been imposed through tachistoscopic presentation (e.g., Townsend, 1971), masking (e.g., Turvey, 1973), or speed stress (e.g., Meyer, Irwin, et al., 1988; Pachella, Smith, & Stanovich, 1978; Wicklegren, 1977). The other class examines priming effects for evidence of response preparation based on partial information (e.g., Meyer et al., 1985; Miller, 1982, 1987; Yantis & Meyer, 1988). An extremely promising advance within this latter class involves the use of movement-related brain potentials to detect response preparation. In particular, a measure of the lateral asymmetry in electrical potential over motor cortex has been used to detect the differential engagement of the two hands (e.g., Coles, 1989; de Jong et al., 1988; Gratton et al., 1988; Miller & Hackley, in press; Mulder, Smid, Wijers, & Mulder, in press; Smid et al., 1990). This measure is called the *lateralized readiness potential* and plays an important role in the study reported below.

As part of these recent developments, we present a new paradigm that uses lateralized readiness potentials to study response preparation based on partial information. In this article, we first describe the paradigm and then demonstrate its usefulness in two experiments. As we hope to show, the paradigm can provide strong and detailed inferences concerning the presence and time course of partial-information transmission. Such inferences enable us to discriminate between several models of task performance that have different implications for the interpretation of reaction times. We also hope to show that the paradigm is quite general. Although the present article deals mainly with partial information from perceptual processes, the paradigm can be used to study the transmission of partial information from other processes as well.

General Approach

We approached the measurement of partial-information transmission by trying to fulfill two requirements. First, we wanted to measure only response preparation arising from identification of the signaled response. Such preparation can be distinguished from preparation that has nothing to do with perception of the response signal (e.g., response bias) or a reaction to stimulus features uncorrelated with the signaled response (e.g., a spelled word in the Stroop paradigm). The second requirement was to be able to distinguish between response preparation based on partial information and response preparation based on complete information (Coles & Gratton, 1986). To satisfy these requirements, we used the lateralized readiness potential (LRP) and a hybrid choice-reaction go/nogo procedure. Each is described separately below.

Lateralized Readiness Potential

The LRP is closely connected with the differential engagement of the two hands. As its name suggests, it is believed to be the lateralized portion of the readiness potential (Coles, 1989; de Jong et al., 1988; Gratton et al., 1988). The readiness potential is a slow negative wave that has been observed preceding spontaneous movements of the distal limbs (Kornhuber & Deecke, 1965; Vaughan, Costa, & Ritter, 1968). The latter part of this wave is largest contralateral to the responding hand and is believed to arise primarily from activity in the precentral motor cortex (Arezzo & Vaughan, 1980; Bashore, McCarthy, Heffley, Clapman, & Donchin, 1982; Brunia, 1980; Deecke, 1987; Kutas & Donchin, 1980; Requin, 1985). Evidence that the LRP reflects movement-related processes will also be presented in the current study.

The LRP is derived as shown in Equation 1:

$$\text{left hand}(C3' - C4') - \text{right hand}(C3' - C4'), \quad (1)$$

where *left* and *right* refer to the hand designated by the response signal, and $C3' - C4'$ is the difference in electrical potential between two electrode sites. These sites are located over the left and right motor cortices and were determined in previous research to have the largest activity when movements of the hand are made (Kutas & Donchin, 1980).[1]

The derivation shown in Equation 1 involves two steps. First, one obtains the waveform corresponding to the difference in electrical potential between the two electrode sites averaged across trials and timed with respect to the response signal. This average waveform is obtained separately for trials on which the response signal indicates left- and right-hand responses. The second step involves subtracting the waveform corresponding to right-hand responses from the waveform

[1] This measure is equivalent to what de Jong, Wierda, Mulder, and Mulder (1988) referred to as the corrected motor asymmetry—right hand($C3' - C4'$) − left hand($C3' - C4'$)—except that it has the opposite polarity. Our version of the LRP is also equivalent to that of Coles (1989) and Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988)—left hand($C4' - C3'$) + right hand($C3' - C4'$)/2—except that it has the opposite polarity and twice the amplitude.

corresponding to left-hand responses. The result is positive if subjects produce greater electrical potential contralateral to the signaled response hand, negative if the electrical potential is greater ipsilateral to the signaled hand, and zero if the potential is unaffected by the identity of the signaled hand.

It is the second step that makes the LRP especially well suited to measure a reaction based on the identification of the signaled response. This subtraction enables differences in potential between the two electrode sites that do not depend on the information conveyed by the response signal to be canceled out. For example, a subject might be biased to prepare a particular response hand before the onset of the response signal, or the class of stimuli used might all tend to engage one hemisphere more than the other. Because these effects would be expected to occur regardless of the signaled hand, they would cancel out. The LRP therefore reflects only that portion of the lateral asymmetry that depends on which hand is signaled.

In the present study, we are especially concerned with the onset of the LRP. This is the first point in time at which one can reliably detect the presence of a positive deviation from zero in the waveform. We argue that by this time differential engagement of the two hands based on the identification of the signaled response must have begun on at least some portion of the trials.

Choice-Reaction Go/Nogo Procedure

To distinguish between response preparation based on partial versus complete information, we tried to create a situation in which only partial information would result in response preparation. To accomplish this, we designed a procedure in which a partial perceptual analysis would suggest that subjects should prepare to respond with one hand or the other, but a more complete analysis would indicate that they should refrain from responding.

The procedure involves a hybrid choice-reaction go/nogo task. In this task, a command signal must be classified along two dimensions, with one involving a more difficult time-consuming discrimination than the other. The outcome of the hard discrimination instructs the subject whether to respond (go–nogo), and the outcome of the easy discrimination tells the subject which hand to use if a response is called for. During each trial, we measure electrical activity at the scalp (electroencephalogram [EEG]), electromyographic (EMG) activity of muscles involved in the signaled responses, and eye movements (electrooculogram [EOG]).

To detect response preparation based on partial information, we observe the behavior of the LRP on nogo trials in which no EMG activity is detected. Even though there are no overt responses on these trials, we label them as left- or right-hand trials on the basis of the response hand signaled by the easy discrimination (Equation 1). The absence of a completed response indicates that subjects ultimately performed the more difficult go/nogo discrimination (or else failed to detect or ignored the command signal). If response preparation occurs only after the signal is evaluated on both dimensions, there would be no reason to deliberately prepare a response hand on these trials. If, however, subjects begin preparing the response hand signaled by the easier discrimination before having completed the more difficult discrimination, we might expect to see the development of a positive LRP.

An important control involves manipulating the duration of the more difficult discrimination. Response preparation detected on nogo trials might be an automatic reaction that occurs after both discriminations are completed, even though subjects know that the response is not called for (Miller, 1987). If response preparation does not begin until both discriminations have been completed, prolonging the duration of the more difficult discrimination should delay its onset. Alternately, the two discriminations might be carried out simultaneously and independently. Then, if subjects begin preparing as soon as they finish the easier discrimination and decide whether to stop or continue after completing the more difficult discrimination, this manipulation should affect the duration of preparation rather than the time at which it begins.

Overview of Experiments

We report two experiments that use the LRP and choice-reaction go/nogo procedure. In the version of the procedure used here, the command signal is an alphanumeric symbol presented to the left or right of a central fixation point. If the symbol is a letter, subjects are supposed to make either a left- or right-hand lever press, depending on its spatial position. If the symbol is a digit, subjects must refrain from responding. The LRP on go (letter) and nogo (digit) trials is obtained by calculating the difference between the lateral asymmetry in electrical potential over motor cortex ($C3' - C4'$) associated with stimuli whose locations signaled left- and right-hand responses (Equation 1).

Besides trying to detect the presence of response preparation based on partial information, we also tried to manipulate its time course. In Experiment 1, we attempted to vary its offset by manipulating the difficulty of the letter/digit discrimination (i.e., how long it took subjects to realize that they could stop preparing the response hand on digit trials). In Experiment 2, we attempted to vary its onset by manipulating the spatial relation (S-R compatibility) between the symbol location and the response hand that it designated. S-R compatibility is believed to affect the duration of processes that precede the preparation of the signaled response (Kornblum, Hasbroucq, & Osman, 1990; Proctor & Reeve, 1990) and thus seemed likely to affect when such preparation would begin.

These two manipulations served as important controls. As mentioned earlier, the manipulation of letter/digit discriminability is necessary to rule out the possibility that LRPs detected on nogo trials arise from an automatic reaction that occurs after perceptual analysis has been completed. The S-R compatibility manipulation allows us to determine whether LRPs on nogo trials arise from a reaction that depends on the particular location of the command signal rather than on the information it conveys (e.g., a tendency to respond toward the signal). Finally, these manipulations were an attempt to influence selectively when preparation of the signaled hand began and ended, and they provided results that allow us to discriminate between several alternative models of information processing.

Experiment 1

In Experiment 1, we sought to determine whether LRPs could occur on nogo trials without overt movement, and if so, how they were affected by the duration of the go/nogo discrimination. Go/nogo discriminability was manipulated by using command signals from two letter/digit pairs. The members of one pair (l/1) were more difficult to tell apart than those of the other pair (V/5). Selection of response hand was based on an easier perceptual discrimination than the go/nogo decision involving either stimulus pair. Left- versus right-hand responses were indicated by whether the command signal occurred on the left or right side of a fixation point.

Method

Subjects. Six healthy adult subjects were each tested individually in a single 2½-hr session. All had normal or corrected-to-normal vision.

Apparatus. Stimuli were presented on a Panasonic W-5410 video monitor at a viewing distance of about 90 cm. Responses were made by rotating one of two 13-cm joysticks that were mounted perpendicularly on platforms on either side of the subject and constrained to move in the coronal plane (left–right). Electrophysiological signals were recorded with Ag/AgCl electrodes and Nicolet EEG1A97 amplifiers. Stimulus presentation and data acquisition were controlled by a DEC PDP 11–73 computer.

Stimuli. The stimuli consisted of a warning signal and four command signals. The warning signal was a star that appeared in the center of the terminal screen and served as a fixation point. The command signals consisted of two letter/digit pairs. The members of one pair, V and 5, were easily discriminable from one another (as well as from the members of the other pair). The other pair, l and 1, were more difficult to tell apart. The stimuli were approximately ⅔° of visual angle high, and the command signals appeared about 2° to the left or right of the warning signal (center to center).

Design. Each combination of stimulus discriminability (easy/hard), stimulus category (letter/digit), and side of presentation (left/right) occurred equally often and in a random order during each block of 104 trials.

Procedure. Subjects were each tested individually in a single session. The session began with a block of practice trials to familiarize them with the choice-reaction go/nogo procedure. They were instructed to respond as quickly as possible, with the constraint that they always respond with the correct hand and on 5% or less of the nogo trials. Electrodes for measuring electrophysiological activity were then applied. A second block of practice trials followed in which subjects learned to minimize their eye movements. The session was completed by having them perform 12 blocks of experimental trials. The blocks each lasted 4½ min and were separated by a pause of approximately 1 min. After the sixth experimental block, subjects were given an additional short break.

Subjects held the joysticks in their hands while resting their forearms (ulnar borders) on the platforms. At the start of each trial, the warning signal appeared at fixation. After 500 ms, the warning signal vanished, and a command signal appeared to the left or the right for 50 ms. If the command signal was a letter, subjects were to respond by moving the lever on the side on which it had appeared. This involved a lateral rotation of the left or right hand and forearm away from the midline. If the command signal was a digit, subjects were to refrain from responding. The onsets of the warning signals on successive trials were separated by an interval of 2,600 ms.

Recording. During each trial, we recorded EEG activity, EOG activity, EMG activity, and the voltage output indicating the displacement of each response lever. These signals were digitized at a rate of 100 Hz for 1,600 ms, starting 100 ms before the presentation of the warning signal and ending 1,000 ms after the presentation of the command signal. Recordings of EEGs were made from the standard midline sites Fz, Cz, and Pz (according to the International 10/20 system, Jasper, 1958), from C3′ and C4′ (approximately 4 cm lateral to Cz along the interaural line) and were referenced to linked mastoids. Bipolar recordings of vertical and horizontal EOGs were made from sites above and below the right eye and 2 cm external to the outer canthus of each eye. Bipolar recordings of EMGs were made from the dorsal surface of each forearm by using standard forearm extensor placements (Lippold, 1967). The electrophysiological signals were filtered during amplification with a bandpass of 0.045–30 Hz for the EEG and EOG and a bandpass of 0.003–120 Hz for the EMG (with 6 and 12 dB per octave roll-offs for the low- and high-frequency cutoffs, respectively).

Results

We are concerned here with several measures: the speed and accuracy of the overt response, the amount of EMG activity, the onset and magnitude of the LRP, and the time at which the LRP began to differ between go and nogo trials. In this section we first provide a general description of how these measures were derived. Results concerning each measure, along with more specific details of their derivation, are then presented separately.

Data reduction. An overt response was considered to have occurred whenever the voltage output indicating the displacement of either lever exceeded a criterion. This criterion was sufficiently strict so that little or no EMG activity was observed on trials in which an overt response was not detected (see EMG results below). Reaction time corresponded to the interval between the onset of the command signal and the time at which the response exceeded the criterion. On those few trials in which multiple responses occurred, only the first was considered. A response on go trials was considered correct if the lever corresponding to the signaled hand exceeded criterion (and did so before the other lever), and a response on nogo trials was considered correct if neither lever exceeded criterion.

The EMG recordings for each trial were rectified (absolute value of voltage taken at every time point) and averaged. These averages where then adjusted by subtracting a baseline voltage from each time point. The baseline corresponded to the average voltage prior to the command signal (i.e., the first 60 time points). The amount of EMG activity following the command signal was assessed by the area under the waveform during the remaining 1 s of the recording epoch (the next 100 time points). Area was calculated by adding the baseline-adjusted voltages at each time point.

LRP waveforms were computed (Equation 1) from the EEG recordings at electrode sites C3′ and C4′ (over the left and right motor cortices) after they were corrected for eye movement artifacts. The correction procedure (Gratton, Coles, & Donchin, 1983) estimated and removed the contribution of both vertical and horizontal eye movements from the potential recorded at each electrode site. Unless otherwise

Table 1
Overt Performance in Experiment 1

	RT_{go}		$P(R)_{go}$		$P(R)_{nogo}$		$P(C \mid R)_{go}$	
Subject	Easy	Hard	Easy	Hard	Easy	Hard	Easy	Hard
1	435	462	1.000	1.000	0.022	0.046	0.967	0.975
2	440	436	0.997	0.988	0.034	0.140	0.967	0.976
3	487	516	1.000	0.984	0.039	0.072	0.962	0.971
4	442	441	1.000	0.976	0.017	0.101	0.991	0.969
5	445	526	1.000	0.924	0.006	0.068	0.959	0.973
6	438	478	0.994	0.981	0.025	0.164	0.990	0.997
M	448	477	0.999	0.976	0.024	0.099	0.973	0.977

Note. RT_{go} denotes reaction time (in milliseconds) on go trials, $P(R)_{go}$ denotes probability of responding on go trials, $P(R)_{nogo}$ denotes probability of responding on nogo trials, and $P(C \mid R)_{go}$ denotes probability that a go-trial response is correct. *Easy* and *Hard* denote easy go/nogo discriminations and hard go/nogo discriminations, respectively.

noted, all LRPs were adjusted by using a baseline corresponding to the average voltage prior to the command signal.[2]

As with the EMG, the magnitude of the LRP was assessed by a measure of area. This area was computed by adding the voltages at each time point within a window. The window began with the presentation of the command signal and ended at the first point in time after LRP onset (see below) at which the waveform was consistently at or below baseline. This later time corresponded to the first point at which the waveform returned to baseline and had an average voltage during the next 100 ms at or below baseline.

The onset of an LRP corresponded to the first point in time at which the waveform achieved a positive amplitude consistently above a criterion. A single criterion of 2.5 times the standard deviation of a noise distribution was applied to the waveform from each of the four experimental conditions. The variance of the noise distribution was estimated by averaging the variances (in voltage over time) of the four waveforms during the baseline interval. To be considered consistently above criterion, the onset and average voltage during each of the next two 50-ms windows had to exceed the criterion. A separate criterion was calculated for the grand averages and the set of four LRPs from each subject.

Finally, go–nogo difference waves were computed by subtracting the LRPs obtained on nogo trials from the LRPs obtained on go trials. This waveform reflects the effect of the go/nogo discrimination on the LRP. When at baseline, it indicates that the LRP is the same for both go and nogo trials. It begins to rise at the time that the LRPs on go and nogo trials begin to diverge, reaches a peak when the LRPs on go and nogo trials are maximally different, and returns to baseline by the time that the LRPs on both trial types have returned to baseline. As with EMG and the LRPs, the difference waves were adjusted by subtracting a baseline that corresponded to the average voltage prior to the command signal. The onset times of the difference waves were determined in the same way as the onset times of the LRPs (see above), except that each criterion was associated with two instead of four waveforms.

Overt performance. Table 1 presents several measures of overt performance for each subject for easy and hard go/nogo discriminations. These include the reaction time on correct go trials, the probability of responding on go trials, the probability of responding on nogo trials, and the proportion of responses on go trials involving the signaled hand. Each measure averaged across subjects is shown at the bottom of the table. It can be seen here that the ease of the go/nogo discrimination affected performance in the expected direction: Subjects were slower on correct go trials for hard than for easy discriminations, mean difference = 29 ms, $t(5) = 2.26$, p(one-tailed) $< .05$; more likely to respond on nogo trials with hard than with easy discriminations, mean difference = 0.075, $t(5) = 3.55$, p(one-tailed) $< .01$; and less likely to respond on go trials with hard than with easy discriminations, mean difference = 0.023, $t(5) = 2.08$, p(one-tailed) $<$ .05. It can also be seen that responses on go trials almost always involved the signaled hand and did not significantly differ in accuracy on trials involving easy and hard go/nogo discriminations, mean difference = 0.004, $t(5) = 0.78$, $p > .4$.

Electromyographic recordings. Figure 1 shows the grand averages of the EMG recordings for easy and hard discriminations on correct go and nogo trials. The vertical and horizontal axes of each graph indicate electrical potential and time, and the dashed lines show the occurrence of the warning and command signals. The main point we wish to make with this figure concerns the lack of EMG activity observed on correct nogo trials (response criterion not exceeded). The area under the curve during the 1 s of recording interval that follows the command signal is hardly different from baseline and is a small proportion of that found on go trials.

Table 2 shows that the pattern above was also evident in the EMG records for individual subjects. Shown here is the EMG area for each subject in each experimental condition. The area averaged across subjects in each condition is shown at the bottom of the table and is the same as that for the grand averages (Figure 1). The mean area on nogo trials did not differ significantly from zero for easy go/nogo discrimina-

[2] The default baseline was slightly different when an LRP or difference wave (see below) received additional off-line filtering. Because the boxcar filter that we used can distort a waveform at the beginning of the recording epoch, only the last 40 points (400 ms) preceding the command signal were used to calculate the baseline.

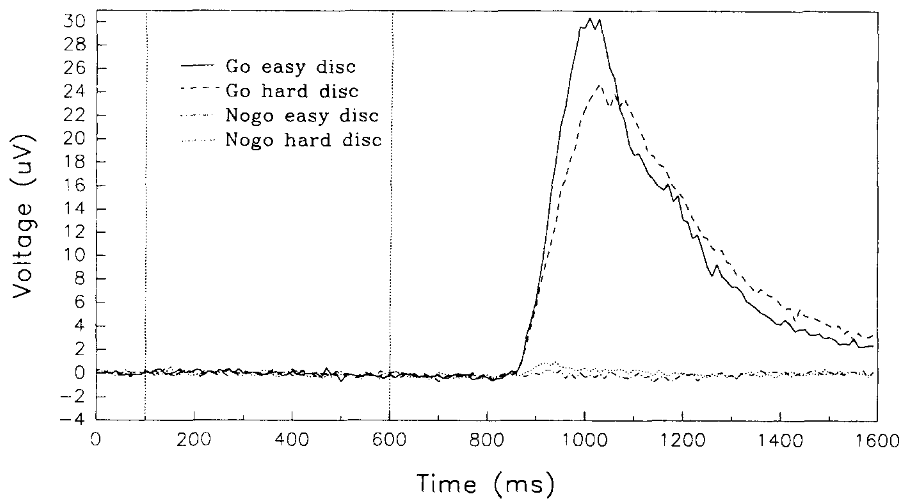

Figure 1. Electromyographic activity on go and nogo trials with easy and hard go/nogo discriminations.

tions, $M = -12.7$ μV, $t(5) = 1.38$, $p > .2$, or hard go/nogo discriminations, $M = 7.3$ μV, $t(5) = 0.57$, $p > .5$. Indeed, for some subjects (negative values), the average amount of EMG activity following the command signal was less than that preceding it. The lack of EMG activity observed on correct nogo trials is important for the interpretation of LRPs on these trials. It shows that the LRPs were not associated with small undetected lever movements and indicates that subjects completed the go/nogo discrimination on these trials.[3]

Lateralized readiness potentials. Figure 2 shows the grand averages of the LRPs for easy and hard discriminations on correct go and nogo trials. Again, the axes indicate voltage and time, and the dashed lines show the onsets of the warning and command signals. We see here that positive waveforms (greater potential contralateral to the signaled hand) begin to develop shortly after the command signal. The onset and initial growth of these waveforms is the same regardless of whether the trial was a go or nogo trial and regardless of the ease of the go/nogo discrimination (onset = 160 ms for each of the four waveforms). After some time, the LRPs on nogo trials diverge from this common growth pattern and return to baseline. This occurs first for nogo trials with easily discriminable command signals and somewhat later for nogo trials with less discriminable command signals. The LRPs on go trials keep growing until about the time of an overt response.

Table 3 shows that the results apparent in the grand averages are also representative of the individual subjects. Shown here for each subject are the onset and area of the LRP in each of the four experimental conditions.[4] The onsets and areas averaged across subjects in each condition are shown at the bottom of the table. It can be seen here that there is an LRP on nogo trials with easy go/nogo discriminations, $M = 25.6$ μV, $t(5) = 3.52$, p(one-tailed) $< .01$, and an LRP on nogo trials with hard go/nogo discriminations, $M = 99.1$ μV, $t(5) = 2.83$, p(one-tailed) $< .02$. An analysis of variance performed on the onsets revealed no main effect of go versus nogo trials, $F(1, 5) = 0.04$, $p > .8$, or go/nogo discriminability, $F(1, 5) = 0.91$, $p > .3$, and no interaction between the two, $F(1, 5) = 0.51$, $p > .5$. Finally, there was significantly more area under the LRP on nogo trials with hard go/nogo discriminations than on nogo trials with easy go/nogo discriminations, mean difference = 73.5 μV, $t(5) = 2.20$, p(one-tailed) $< .05$.

Table 2
Electromyograph (EMG) Area Following Command-Signal Presentation in Experiment 1

	Easy discrimination		Hard discrimination	
Subject	Go	Nogo	Go	Nogo
1	900.5	−21.9	886.6	−9.5
2	579.8	2.7	578.3	−30.7
3	673.2	−32.4	653.2	−9.2
4	761.8	14.2	740.1	59.9
5	880.0	3.1	888.5	19.8
6	1,257.7	−41.7	1,281.7	13.4
M	842.2	−12.7	838.1	7.3

Note. Area values correspond to the sum of the EMG magnitudes (μV) at the time points sampled (100 Hz) during the 1 s following command-signal presentation. Negative values indicate that the average EMG magnitude was less than during the baseline period.

[3] We cannot claim that there was absolutely no increase in EMG activity during correct nogo trials. Activity of muscles indirectly involved in the signaled response (e.g., in postural adjustments) might not have been detected. However, the apparent lack of EMG activity is sufficient to demonstrate that an LRP on nogo trials could not arise from completed responses. Such responses might occur if subjects occasionally neglected to perform the go/nogo discrimination or heed its outcome.

[4] Before calculating the values in Table 3, the LRPs for Subjects 5 and 6 were processed further. To compensate for drift, the LRPs for Subject 5 were adjusted by subtracting a baseline corresponding to the average voltage during the 50 ms preceding and following the command signal. The LRPs for Subject 6 were smoothed with a low-pass digital filter with a high-frequency cutoff of 3.4 Hz.

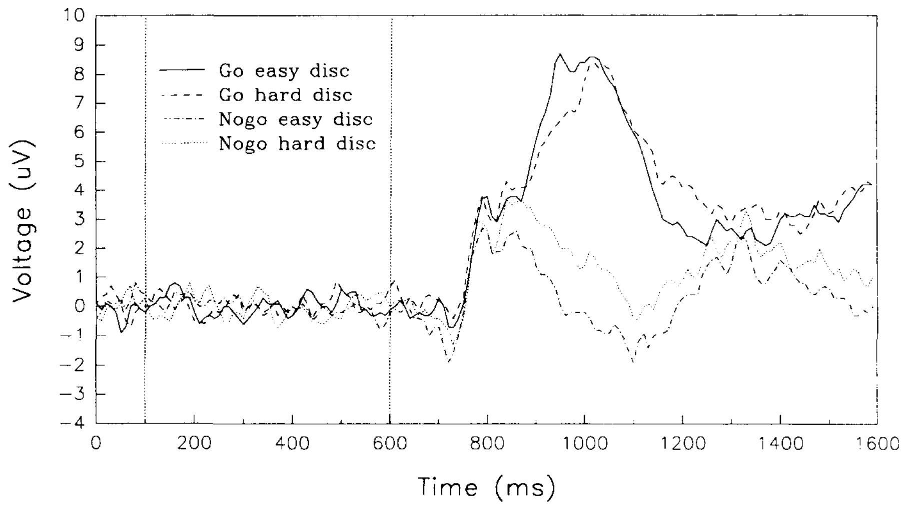

Figure 2. Lateralized readiness potentials on go and nogo trials with easy and hard go/nogo discriminations.

Go–nogo difference waves. Figure 3 presents the grand average waveforms of the difference between go and nogo trials with easy and hard go/nogo discriminations. Axes indicate time and voltage, and the dashed lines show the onsets of the warning and command signals. These waveforms are based on all trials (both correct and error) and are approximated by the difference between each pair of go and nogo waveforms in Figure 2 (which are based on correct trials only).[5] The onsets of these waveforms correspond to the time at which go and nogo LRPs begin to differ in their amplitude and reflect the effects of the go/nogo discrimination on response preparation. We see here that the difference waveform for easy go/nogo discriminations has an earlier onset (190 ms) than does the waveform for hard go/nogo discriminations (290 ms).

Table 4 presents the onsets of the difference waves for easy and hard go/nogo discriminations for each subject.[6] The onset of the difference wave averaged across subjects for each level of discriminability is shown at the bottom of the table. We see here that the pattern found in the grand averages is also evident in the waveforms for individual subjects. In each case, the waveform corresponding to easy go/nogo discriminations had an earlier onset than the waveform corresponding to hard go/nogo discriminations, mean difference = 44 ms, $t(5) = 3.03$, p(one-tailed) $< .02$.

Discussion

The principal findings of Experiment 1 concern the LRP. We found an LRP on nogo trials without apparent EMG activity and that the amount of LRP was greater for difficult nogo discriminations than for easy ones. We also found that LRP onset was the same on correct go trials and nogo trials and that it was unaffected by the difficulty of the go/nogo discrimination. Finally, we found that the time at which the LRPs on go and nogo trials began to differ (onset of the go–nogo difference wave) was later for difficult go/nogo discriminations than for easy ones.

Given these findings, one might be tempted to conclude that subjects began preparing response hand before completing the go/nogo discrimination. The lack of apparent EMG activity on correct nogo trials indicates that subjects did complete the go/nogo discrimination. If response preparation occurred only after the command signal was evaluated on both dimensions, there would have been no need for subjects to deliberately prepare a response hand on these trials. Nevertheless, we did find an LRP.

However, before reaching any definite conclusions concerning LRPs on nogo trials, it is necessary to consider some alternative interpretations of this finding. One possibility is that it reflects an automatic response that occurred after both the left/right and go/nogo discriminations had been completed. Even if response preparation did not begin until both discriminations had been completed, subjects might not have been able to resist preparing the signaled response hand on nogo trials.

The results concerning the time course of the LRP allow us to rule out this hypothesis. The difficulty of the go/nogo discrimination had no effect on the onset of the LRPs on

[5] We included both correct and error trials to ensure that the difference waveforms reflected only a differential response to go and nogo command signals. Excluding detected errors could produce selection artifacts because different types of errors (e.g., preparing the wrong hand or ignoring the go/nogo stimulus attribute) are not equally observable on go and nogo trials. Note, however, that go–nogo waveforms based only on correct trials yielded results very similar to those based on all trials.

[6] Before the values in Table 4 were calculated, the go–nogo difference waves for individual subjects were smoothed with a low-pass digital filter with a high-frequency cutoff of 6.2 Hz. To compensate for drift, the waveforms for Subjects 1 and 3 were adjusted by subtracting a baseline corresponding to the average voltage during the 200 ms following the command signal.

Table 3
Lateralized Readiness Potential (LRP) Area[a] and Onset (in Milliseconds) in Experiment 1

	Area				Onset			
	Easy discrimination		Hard discrimination		Easy discrimination		Hard discrimination	
Subject	Go	Nogo	Go	Nogo	Go	Nogo	Go	Nogo
1	251.5	47.4	401.7	88.3	170	170	160	170
2	151.3	2.8	136.7	61.7	180	240	230	170
3	412.1	27.3	507.8	251.5	170	170	170	170
4	217.0	30.1	144.2	23.1	160	150	150	150
5	556.3	39.7	620.5	139.3	150	140	160	160
6	226.4	6.3	172.7	30.9	140	160	160	180
M	302.4	25.6	330.6	99.1	162	172	172	167

[a] Area values correspond to the sum of the LRP magnitudes (μV) at the time points sampled (100 Hz) within a temporal window (see the *Results* section of Experiment 1 for definition of window).

either go or nogo trials. Thus, prolonging the more difficult discrimination did not delay response preparation, as would have been expected if response preparation could not begin until both discriminations were completed. Instead, it delayed the onset of the go–nogo difference wave, as might be expected if the outcome of the go/nogo discrimination instructed subjects to continue or inhibit ongoing response preparation.

Another possibility is that LRPs on nogo trials reflected something other than preparation of the signaled hand. By virtue of its derivation, the LRP is a differential response to stimuli that signal the left versus the right hand. This information was conveyed by command signal location. Perhaps the mapping between signal location and response hand involved a fortuitous coincidence that allowed a reaction to the mere presentation of a stimulus at a particular location to masquerade as response preparation based on information conveyed by the signal. For example, LRPs on nogo trials might reflect an automatic tendency to prepare the hand on the same side as the command signal (Kornblum et al., 1990; Simon, 1969) or might result from eye movements to fixate the command signal.

These hypotheses are also difficult to reconcile with the effects of go/nogo discriminability on the duration of nogo LRPs. It might be argued that subjects spent more time fixating the less discriminable command signals. This is unlikely because the duration of the command signal (50 ms) was less than the time necessary to complete most saccades. Also, recall that eye movement artifacts were removed by the eye movement correction procedure (Gratton et al., 1983). Nevertheless, more direct evidence concerning possible responses to the mere presentation of a stimulus at a particular location would be helpful. Experiment 2 was therefore designed to disassociate the location of the command signal and the identity of the signaled response. By manipulating the relation between the two, we hoped to determine the relative contribution of each to the LRPs observed on nogo trials.

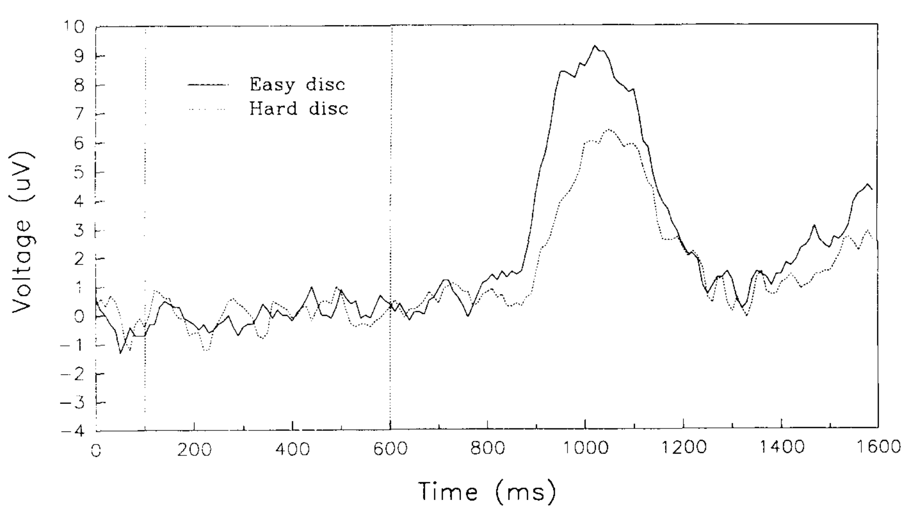

Figure 3. Go–nogo difference waves for easy and hard go/nogo discriminations.

Table 4
Onset (in Milliseconds) of Go–Nogo Difference Waveforms in Experiment 1

Subject	Easy discrimination	Hard discrimination
1	290	310
2	290	330
3	280	320
4	190	200
5	160	200
6	220	330
M	238	282

Experiment 2

In Experiment 2 we manipulated the spatial relation between the command signal and the signaled response. This relation could be either compatible or incompatible. As in Experiment 1, response hand was designated by the spatial location of the command signal, which occurred to the left or right of a central fixation point. In compatible conditions, a signal on the left indicated a response with the left hand, and a signal on the right indicated a response with the right hand. In incompatible conditions, the mapping between signal location and response hand was reversed.

The S-R compatibility manipulation was motivated by two objectives. First, it allowed us to determine whether the LRPs on nogo trials reflect a process whose laterality depends on the location of the command signal or on the signaled response hand. The compatible condition replicates the spatial relation between the command signal and response hand in Experiment 1. The positive LRP observed in Experiment 1 indicates a greater electrical potential contralateral to both the command signal and response hand (Equation 1). In the incompatible condition, the command signal and signaled response occur on opposite sides. Because it is calculated on the basis of response hand, the LRP on incompatible nogo trials will still be positive if its laterality depends on response hand but negative if its laterality depends on signal location.

The second objective was to determine whether the onsets of the LRP and go–nogo difference wave could be selectively influenced by factors expected to selectively influence the onset and offset of response preparation. In Experiment 1, we observed that the onset of the go–nogo difference wave was affected by the difficulty of the go/nogo discrimination, a factor that might be expected to influence the time at which subjects realized that they could stop preparing a response hand on nogo trials. In contrast, the S-R compatibility manipulation seemed likely to affect the duration of processes that precede preparation of the signaled hand (Kornblum et al., 1990; Proctor & Reeve, 1990) and thus when this preparation would begin. Because preparation of the signaled hand might be delayed on incompatible trials, we made the go/nogo discrimination especially difficult to ensure that partial information would have an opportunity to affect response processes before nogo trials could be identified.

Method

Subjects. Six healthy adult subjects were each tested individually in a 2½-hr session. All had normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus was the same as in Experiment 1. The stimuli again consisted of two letters, two digits, and a warning signal. The warning signal (*) and one letter/digit pair (1/1) were the same as in Experiment 1. The other letter/digit pair consisted of a lowercase letter gee and the number nine. The latter pair was drawn so that each of the four command signals could only be classified as a letter or digit by discriminating and conjoining the values of two features: whether it had a box at the top and whether a small line extending from the stem was horizontal or diagonal. The digits had either a box and a horizontal line or no box and a diagonal line. The letters had either a box and a diagonal line or no box and a horizontal line.

Design. Each combination of stimulus category (letter/digit) and side of presentation (left/right) occurred equally often during each block of 152 trials. Compatible and incompatible mappings between the command signal and response hand were alternated between blocks, with the order of presentation balanced across subjects.

Procedure. The trial-by-trial procedure and instructions were the same as in Experiment 1. Subjects were given three blocks of practice trials. During the first block, they merely named each letter or digit as it appeared on the screen. Electrodes for measuring electrophysiological activity were then applied. Subjects next received one block of practice in the experimental procedure with each of the two S-R mappings, while also learning to minimize their eye movements. Finally, subjects received six blocks of experimental trials. The blocks each lasted approximately 6½ min and were separated by a 1-min

Table 5
Overt Performance in Experiment 2

Subject	RT_{go}		$P(R)_{go}$		$P(R)_{nogo}$		$P(C\mid R)_{go}$	
	Compatible	Incompatible	Compatible	Incompatible	Compatible	Incompatible	Compatible	Incompatible
1	564	589	0.900	0.941	0.068	0.089	0.971	0.963
2	508	516	1.000	1.000	0.078	0.051	0.973	0.995
3	522	516	0.984	0.995	0.131	0.138	0.962	0.985
4	579	610	0.980	0.952	0.042	0.066	0.974	0.970
5	580	598	0.986	0.991	0.143	0.072	0.947	0.971
6	606	626	0.964	0.974	0.048	0.038	0.996	0.996
M	560	576	0.969	0.976	0.085	0.076	0.971	0.980

Note. RT_{go} denotes reaction time (in milliseconds) on go trials, $P(R)_{go}$ denotes probability of responding on go trials, $P(R)_{nogo}$ denotes probability of responding on nogo trials, and $P(C\mid R)_{go}$ denotes probability that a go-trial response is correct. *Compatible* and *Incompatible* denote compatible and incompatible mapping, respectively.

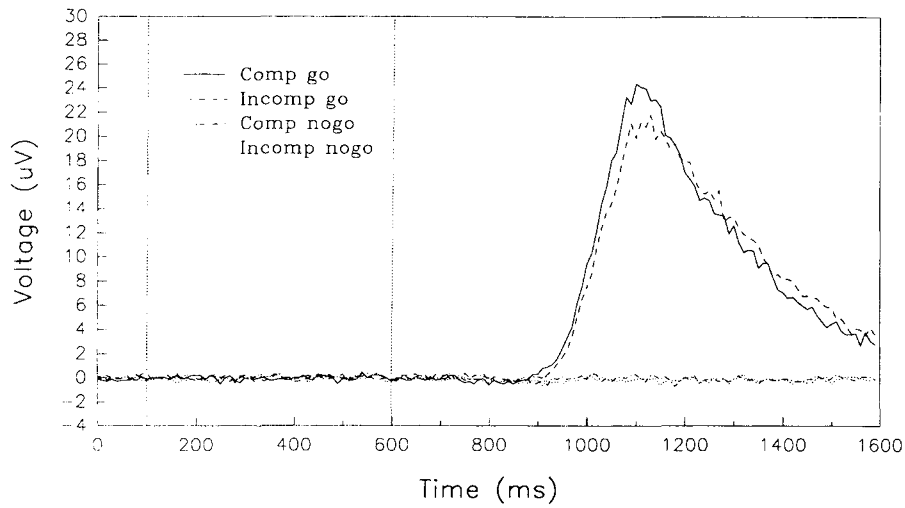

Figure 4. Electromyographic activity on go and nogo trials with compatible and incompatible S-R mappings.

pause. After three blocks, subjects were given an additional short break. To minimize transfer effects between blocks with different S-R mappings, the first 25 trials of each block were not included in the data analysis.

Recording. The recording of EEG, EOG, EMG, and response-lever displacement was the same as in Experiment 1.

Results

We are concerned here with the same measures as in Experiment 1: the speed and accuracy of the overt response, the amount of EMG activity, the onset time and magnitude of the LRP, and the time at which the LRP began to differ between go and nogo trials. These measures were derived as described in Experiment 1 (*Results* section), and the results concerning each are discussed separately below.

Overt performance. Table 5 presents several measures of overt performance for each subject in each mapping condition. These include the reaction time on correct go trials, the probability of responding on go trials, the probability of responding on nogo trials, and the proportion of responses on go trials involving the signaled hand. Each of these measures averaged across subjects is shown at the bottom of the table. It can be seen here that the S-R compatibility manipulation had a modest effect on reaction time in the predicted direction. Correct responses on go trials were slightly faster with compatible than with incompatible mappings, mean difference = 16 ms, $t(5) = 2.96$, $p(\text{one-tailed}) < .02$. The S-R compatibility manipulation had little effect on the probability of responding on either go trials, mean difference = 0.007, $t(5) = 0.72$, $p > .5$, or nogo trials, mean difference = 0.009, $t(5) = 0.64$, $p > .5$. Responses on go trials almost always involved the signaled hand and did not significantly differ in accuracy on trials with compatible and incompatible mappings, mean difference = 0.009, $t(5) = 1.55$, $p > .1$.

Electromyographic recordings. Figure 4 shows the grand averages of the EMG recordings for correct go and nogo trials with compatible and incompatible mappings. The axes indicate time and voltage, and the dashed lines show the occurrence of the warning and command signals. As in Experiment 1, we observed little EMG activity on correct nogo trials. The area under nogo waveforms following the command signal is barely different from zero, and if anything, slightly less. As mentioned previously, a negative area indicates less EMG activity following the command signal than during the baseline period.

Table 6 shows that this pattern was evident in the EMG records of the individual subjects. Shown here is the area for each subject in each experimental condition. The area averaged across subjects in each condition is shown at the bottom of the table and is the same as that for the grand averages (Figure 4). The mean area under the waveform on nogo trials did not differ significantly from zero in the compatible condition, $M = -10.2$ μV, $t(5) = 1.13$, $p > .3$, and was significantly less than zero in the incompatible condition, $M = -13.6$ μV, $t(5) = 4.64$, $p < .01$.

Table 6
Electromyograph (EMG) Area Following Command-Signal Presentation in Experiment 2

	Compatible		Incompatible	
Subject	Go	Nogo	Go	Nogo
1	715.8	−10.6	576.3	−16.9
2	846.3	−39.8	874.4	−22.3
3	1,162.5	−18.1	1,242.8	−6.7
4	744.9	28.0	768.1	−7.8
5	566.7	−14.7	508.2	−20.5
6	472.0	−5.7	448.8	−7.2
M	751.4	−10.2	736.4	−13.6

Note. Area values correspond to the sum of the EMG magnitudes (μV) at the time points sampled (100 Hz) during the 1 s following command-signal presentation. Negative values indicate that the average EMG magnitude was less than during the baseline period.

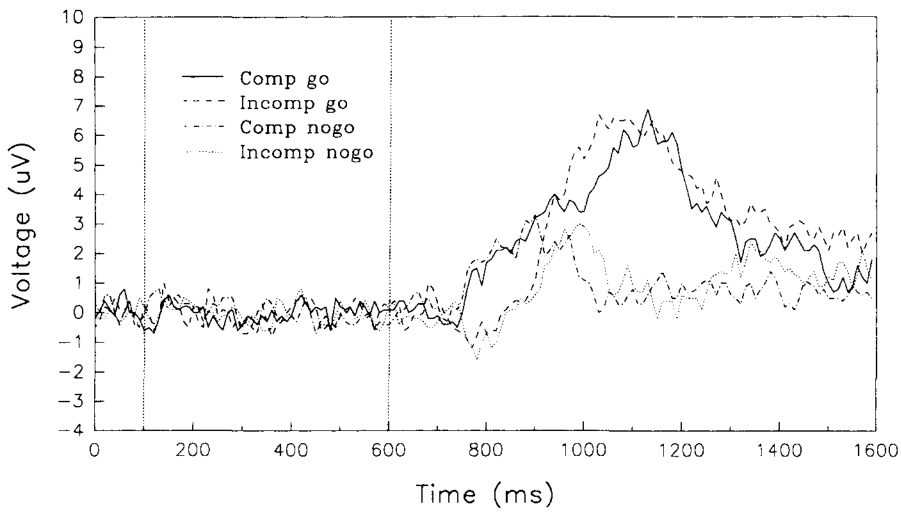

Figure 5. Lateralized readiness potentials on go and nogo trials with compatible and incompatible S-R mappings.

Lateralized readiness potential. Figure 5 shows the grand averages of the LRPs for correct go and nogo trials with compatible and incompatible mappings. The axes indicate time and voltage, and the dashed lines show the onsets of the warning and command signals. We see here a predominantly positive LRP (greater potential contralateral to the signaled hand) on each trial type. Although there are small initial negative deflections on incompatible go and nogo trials (greater potential contralateral to the command signal), they are followed by much larger positive waveforms.[7] The initial development of the positive LRP (LRP onset) occurs first on compatible go and nogo trials (160 ms and 150 ms) and then on incompatible go and nogo trials (260 ms and 270 ms). Next, go and nogo LRPs begin to differ in their rate of growth. Although the LRPs on nogo trials continue to grow for a while, they do not reach the level of the LRPs on go trials and return to baseline sooner.

Table 7 shows that the results apparent in the grand averages are also representative of the individual subjects. Shown here for each subject are the onset and area of the LRPs in each experimental condition.[8] The average for each condition is shown at the bottom of the table. The area under the LRP (including any negative deflection) was positive and significantly greater than zero on both compatible nogo trials, $M = 94.2\ \mu V$, $t(5) = 3.36$, $p(\text{one-tailed}) < .01$, and incompatible nogo trials, $M = 65.7\ \mu V$, $t(5) = 2.73$, $p(\text{one-tailed}) < .02$. An analysis of variance performed on the onsets revealed a main effect of S-R compatibility, $F(1, 5) = 51.70$, $p < .001$, but no main effect of whether the trial was a go or nogo trial, $F(1, 5) = 0.005$, $p > .9$, or an interaction between these two factors, $F(1, 5) = 1.05$, $p > .3$.

Go–nogo difference waves. Figure 6 presents the grand average waveforms for the difference between the LRPs on go and nogo trials in each compatibility condition. The axes indicate time and voltage, and the dashed lines show the onsets of the warning and command signals. The S-R compatibility manipulation did not appear to affect the divergence of LRPs on go and nogo trials. The two difference waves are virtually identical, as is reflected in their onsets (320 ms for compatible and 310 ms for incompatible).

Table 8 shows that this pattern characterizes the go–nogo difference waves for individual subjects. Shown here for each subject are the onsets of the difference waves for compatible and incompatible mappings.[9] The onsets averaged across subjects for each mapping are shown at the bottom of the table. The onsets of the two difference waves did not differ significantly from one another, mean difference = 3 ms, $t(5) = 0.38$, $p > .7$.

[7] This negative deflection was apparent in the LRPs on incompatible go and nogo trials for all subjects and began at approximately the same time as the positive deflection on compatible trials. An analysis of variance (see Footnote 8) found the waveforms on incompatible trials to be significantly negative in the region between 150 and 250 ms after the command signal, $M = -0.68\ \mu V$, $F(1, 5) = 10.627$, $p(\text{one-tailed}) < .02$, with no effect of whether the trial was a go or nogo trial, mean difference = $0.072\ \mu V$, $F(1, 5) = 0.26$, $p > .8$.

[8] Before the values in Table 7 (and the analysis of variance in Footnote 7) were calculated, the LRPs for Subjects 5 and 6 were processed further. To compensate for drift, the LRPs for Subject 5 were adjusted by subtracting a baseline corresponding to the average voltage during the 100 ms following the command signal, and the LRPs for Subject 6 were adjusted by subtracting a baseline corresponding to the average voltage during the 200 ms preceding the command signal. The LRPs for both subjects were smoothed with a low-pass digital filter with a high-frequency cutoff of 4.4 Hz.

[9] Before the values in Table 8 were calculated, the go–nogo difference waves for individual subjects were smoothed with a low-pass digital filter with a high-frequency cutoff of 6.2 Hz. To adjust for drift, the waveforms for Subject 4 were adjusted by subtracting a baseline corresponding to the average voltage during the interval from 200 to 350 ms after the command signal.

Table 7
Lateralized Readiness Potential (LRP) Area[a] *and onset (in Milliseconds) in Experiment 2*

	Area				Onset			
	Compatible		Incompatible		Compatible		Incompatible	
Subject	Go	Nogo	Go	Nogo	Go	Nogo	Go	Nogo
1	287.2	156.1	212.3	153.1	140	140	230	240
2	226.5	124.2	221.4	109.0	170	190	280	340
3	244.9	90.0	208.4	29.9	150	150	310	300
4	544.6	168.8	528.3	3.2	160	160	320	360
5	129.2	14.2	193.4	82.2	200	140	280	240
6	128.0	11.7	176.6	17.0	180	190	270	250
M	260.1	94.2	256.7	65.7	167	162	282	288

[a] Area values correspond to the sum of the LRP magnitudes (μV) at the time points sampled (100 Hz) within a temporal window (see the *Results* section of Experiment 1 for definition of window).

Discussion

The results of Experiment 2 both replicate and extend those of Experiment 1. We again found LRPs on nogo trials without apparent EMG activity. Moreover, the polarity of this waveform was determined primarily by the response side designated by symbol location, rather than the actual location in which the symbol occurred. We also again found similar onsets for LRPs on go and nogo trials. These onsets, however, were affected by the spatial compatibility between the location of the command signal and the signaled response. Finally, the S-R compatibility manipulation did not affect the onset of the go–nogo difference wave.

These results allow us to reject several lines of explanation for the occurrence of LRPs on nogo trials. One class of explanation (Experiment 1, *Discussion* section) attributes these potentials to a reaction that depends on signal location per se rather than to response preparation based on information conveyed by location. Such explanations imply that the LRPs on incompatible nogo trials should have a negative polarity (Equation 1). Yet, these potentials were found to be predominantly positive, just as on compatible nogo trials.

Another possible explanation for the LRPs on nogo trials posits a model composed of four serial stages. According to this model, stimulus evaluation and response preparation each consist of two substages. Although response preparation begins before stimulus evaluation is completed, these substages actually have no temporal overlap. More specifically, subjects first locate the command signal, next prepare the designated response, then perform the go/nogo discrimination, and finally execute or inhibit the prepared response. The LRPs on nogo trials and the early portion of the LRP on go trials are associated with the second stage in this sequence. The go–nogo difference wave and the latter portion of the LRP on go trials are associated with the fourth stage. If this model were true, it would still be possible to conceive of reaction time on go trials as the sum of a set of stage durations.

The model described above can be ruled out by the pattern of effects of the S-R compatibility manipulation on the time course of the LRP. By definition, all serial stage models predict

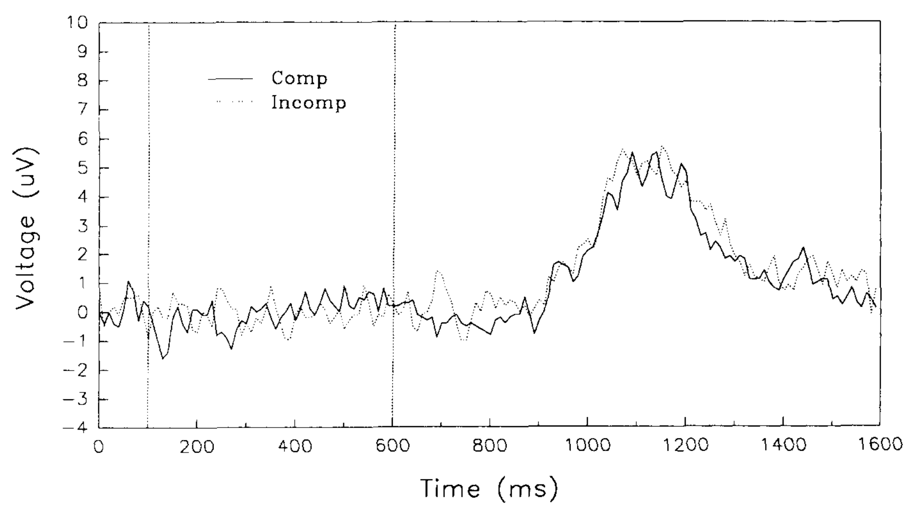

Figure 6. Go–nogo difference waves for compatible and incompatible S-R mappings.

Table 8
Onset (in Milliseconds) of Go–Nogo Difference Waveforms in Experiment 2

Subject	Compatible	Incompatible
1	330	340
2	320	300
3	400	390
4	340	350
5	360	400
6	350	340
M	350	353

that delaying the onset or duration of a stage will delay the onset of all subsequent stages. In the model described above, LRP onset indicates the beginning of one stage, and the onset of the go–nogo difference wave indicates the beginning of a later stage. Thus, according to this model, any factor that delays the former measure should also delay the latter. Yet we found that S-R compatibility affected LRP onset on go and nogo trials but did not affect the onset of the go–nogo difference wave. This result indicates that there must be temporal overlap between the processes that give rise to a positive LRP and the processes that cause it to diverge on go and nogo trials.[10]

Finally, in addition to demonstrating the temporal overlap of these processes, our results indicate that they can be separately influenced. The selective effect of the S-R compatibility manipulation on LRP onset nicely complements the selective effect of go/nogo discriminability on the onset of the go–nogo difference wave. Together, these results provide a double dissociation between the chain of events leading from one stimulus attribute to LRP onset and the chain of events leading from another stimulus attribute to LRP divergence on go and nogo trials. Moreover, inasmuch as the factors manipulated in Experiments 1 and 2 might be expected to influence the time course of response preparation, they support our interpretation of the LRP as reflecting such preparation.

General Discussion

We have presented a new paradigm for studying response preparation based on partial information. The paradigm involves measuring LRPs during a hybrid choice-reaction go/nogo task in which decisions about response hand and whether to respond are based on separate stimulus attributes. By observing LRPs on nogo trials in which subjects refrain from responding and comparing these waveforms with those on go trials, it is possible to determine when the information conveyed by each stimulus attribute influences response-preparation processes.

Our aim was to demonstrate the validity and sensitivity of the paradigm and to demonstrate the types of inferences that it makes possible. To accomplish this, we created a situation in which partial-information transmission might occur and tried to manipulate its time course. We then observed whether the paradigm yielded the predicted pattern of results and evaluated alternative interpretations of these results. Of course, the ultimate purpose of the paradigm is to detect partial-information transmission and to determine its time course under less predictable circumstances. It was first necessary, however, to test the paradigm under conditions in which such inferences could be confirmed.

Experiments 1 and 2 yielded five major findings. First, we observed LRPs on nogo trials without apparent muscle activity. Second, the direction of the lateral asymmetry depended primarily on the designated response hand rather than the location at which the command signal occurred. Third, the LRP began to develop at approximately the same time on correct go and nogo trials. Fourth, go/nogo discriminability affected when the LRP began to differ on go and nogo trials but not when it first appeared. Finally, the S-R compatibility manipulation affected when a positive LRP first appeared but not its differential development on go and nogo trials.

These findings support two conclusions. First, LRPs on nogo trials reflected the differential engagement of the two hands. A greater electrical potential was found contralateral to the signaled hand, regardless of the location of the command signal. Moreover, the time course of this potential was affected in the predicted manner by manipulations expected to affect the time course of response preparation.

The second conclusion is that preparation of the signaled hand occurred in parallel with the continued perceptual analysis of the command signal. This conclusion can be better understood by considering Figure 7. The figure shows three alternative models of performance in the choice-reaction go/nogo procedure.

The top panel contains a two-stage model in which response preparation follows the complete analysis of both stimulus attributes. As mentioned (Experiment 1, *Discussion* section), this model can be rejected because we found LRPs on nogo trials without apparent EMG activity, and because LRP onset time did not depend on the duration of the go/nogo discrimination.

The middle panel of the figure presents a more complex serial stage model. According to this model, subjects first discriminate the left/right stimulus feature, next prepare the signaled response hand, then discriminate the go/nogo feature, and finally either execute or inhibit the prepared response. Here, LRP onset is associated with the start of the second stage, and the onset of the go–nogo difference wave is associated with the start of the fourth stage. As mentioned (Experiment 2, *Discussion* section), this model is ruled out because the S-R compatibility manipulation delayed LRP onset without delaying the onset of the go–nogo difference wave. This result indicates that there must be temporal over-

[10] As noted, the early negative deflection on incompatible trials might reflect automatic preparation of the incorrect response hand (Kornblum, Hasbroucq, & Osman, 1990; Simon, 1969). Response preparation might then begin at the same time on both compatible and incompatible trials (see Figure 5). If this were the case, the effect of S-R compatibility on (positive) LRP onset would imply a change in the duration of the second stage rather than its onset. The four-stage model would thus still predict a delay in the stage associated with the go–nogo difference wave.

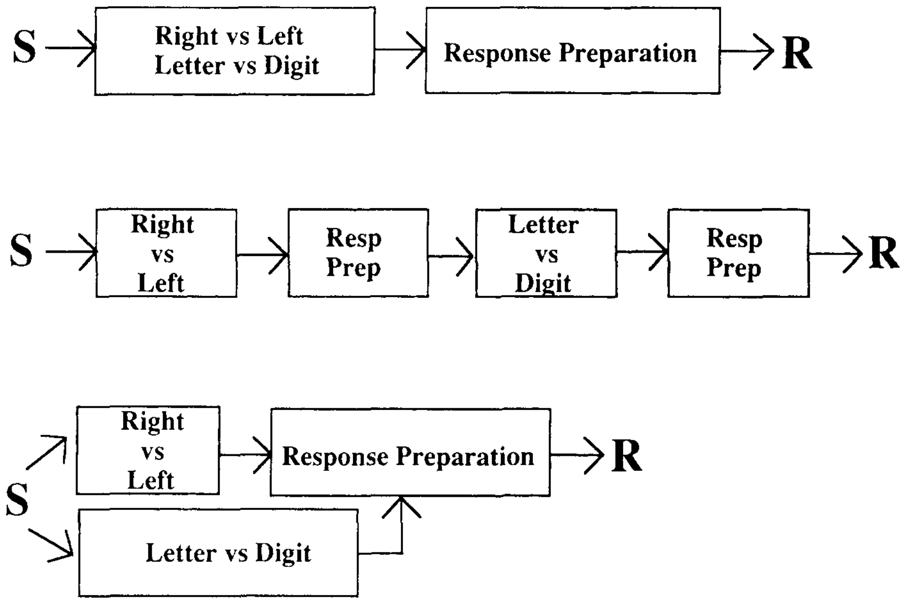

Figure 7. Alternative models of performance in the choice-reaction go/nogo procedure.

lap between the processes that give rise to a positive LRP and the processes that cause it to develop differently on go and nogo trials.

This leaves us with the model outlined in the bottom panel. The model involves two cases of temporal overlap. The go/nogo discrimination occurs in parallel with the left/right discrimination and with preparation of the signaled response hand. At present, the form of information transmission between these processes remains unspecified. This transmission could either be all-or-none (Sanders, 1980; Sternberg, 1969), involve several discrete quanta (Miller, 1982), or occur continuously (Eriksen & Schultz, 1979; McClelland, 1979).

Our conclusions concerning the temporal overlap of processes bear on the interpretation of reaction times. According to the method of additive factors, an interaction between different experimental manipulations implies that they affect a common serial stage (Sanders, 1980; Sternberg, 1969). With the possible exception of early perceptual and late response processes, none of the processes underlying performance in the choice-reaction go/nogo procedure could be conceived of as composing a separate serial stage. Rather, they are all part of a single serial stage that extends over much of the RT interval. Experimental manipulations could therefore interact in their effects on reaction time, even though they selectively influenced the duration of processes as functionally distinct as stimulus discrimination and response preparation. Under other conditions, however, the paradigm could yield results that support either of the models shown in the top two panels of Figure 7. An analysis of interactions could then be used to identify and study serial stages corresponding to more specific components of the information-processing system.

The present findings are most relevant to tasks in which a response requires the integration of multiple decisions, each concerning a different stimulus attribute. In many reaction time tasks, however, the response is based on a single classification of the stimulus. Miller (1988b) suggested that partial-information transmission may be detected under such circumstances by basing both the response hand and go/nogo decisions on the same stimulus dimension. Response hand could be based on a very crude discrimination, and the go/nogo decision could require a more precise discrimination. If the same process could be shown to underlie the two discriminations, it would then be possible to determine whether response preparation based on the early output of this process occurred in parallel with its continued operation.

Our results also show how the paradigm can be used to study perceptual processes and representations. We were able to observe separately the times at which the two discriminations had an impact on preparatory processes. This allowed a double dissociation in which these times were selectively affected by different experimental manipulations. This dissociation suggests the existence of two sets of distinct processes operating on separable stimulus dimensions (Garner, 1970) that do not compete for limited attentional resources (Navon & Gopher, 1979). Moreover, Miller (1982, 1983, 1988a) argued that the transmission of partial information requires a discrete code by which the information can be represented (Posner, 1978). In this view, our finding of response preparation based on signal location would imply that location is being represented in terms of a discrete code (e.g., left/right), separable from alphanumeric category.

Having been tested in somewhat sheltered waters, the paradigm may now provide a fit vehicle for more far-reaching and ambitious explorations. For example, it might be used to study the processes involved in reading or other linguistic activities. Left/right and go/nogo decisions could involve classifying words according to their orthography, phonology, or meaning at various levels of abstraction. Such studies might help reveal whether the meaning of a word can be activated by partial information concerning individual letters (Mc-

Clelland & Rumelhart, 1981) or if different meanings of a word can be activated simultaneously (Schvaneveldt, Meyer, & Becker, 1976; Swinney, 1979; Van Petten & Kutas, 1987). It is also possible to manipulate the type or extent of the operations involved in the left/right and go/nogo decisions. For example, these decisions could depend on the outcomes of comparisons, transformations involving imagery, arithmetic calculations, or real-world judgments. In this way, one could perhaps discover whether the processes underlying these operations produce intermediate results.

In conclusion, this study provides another example of how psychophysiological measures may bear on issues within cognitive psychology. It represents a further development in the emerging synthesis between two research traditions: mental chronometry based on measures of reaction time and cognitive psychophysiology based on measures of endogenous event-related brain potentials (Coles, 1989; Meyer, Osman, et al., 1988; van der Molen et al., 1991). Our results illustrate how the LRP can be used to make detailed inferences concerning the time course of response preparation. By combining LRPs with the choice-reaction go/nogo procedure, we were able to examine separately the onset and offset of response preparation as well as the time at which response preparation was affected by separate decisions based on different stimulus attributes. Such inferences may be germane to many issues central to the study of mental chronometry besides the transmission of partial information. The LRP may therefore help provide the additional "degrees of freedom" necessary to make progress on a number of problems whose solutions have so far eluded reaction time measures alone.

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