Bisecting RT with lateralized readiness potentials: Precue effects after LRP onset

Allen Osman a, *, Cathleen M. Moore b, Rolf Ulrich c

a Department of Psychology, 0109, University of California at San Diego, La Jolla, CA 92093-0109, USA
b Johns Hopkins University, Baltimore, MD, USA
c University of Wuppertal, Wuppertal, Germany

Abstract

Recent work has sought to use the time at which the Lateralized Readiness Potential (LRP) first develops (LRP onset) as a temporal landmark to bisect experimental effects on reaction time (RT). Many studies have found experimental effects on the time between the signal and LRP onset, but few have found effects on the time between LRP onset and RT (LRP-RT interval). The primary goal of this study was to produce an effect on the LRP-RT interval. We employed precuing, a manipulation likely to influence motor-programming processes at the end of the RT interval. Subjects performed a 4-alternative choice-RT task in which a signal prompted a button-press with the index or middle finger on the left or right hand. Precues preceded the signals and were either informative, reducing the set of response alternatives from four to two, or uninformative. Besides RT and LRP, we also measured electromyographic (EMG) activity and the P300 ERP component. RT, P300 latency, and the interval between the signal and LRP onset were all shorter with informative than uninformative precues, but the timing of EMG activity relative to RT remained the same. Most importantly, precuing affected the LRP-RT interval. Implications for bisecting RT with LRPds and the identity of processes affected by precuing are discussed.

1. Introduction

It is most fitting that the KNAW Symposium on Discrete versus Continuous Processes was held in the very same room where Donders (1868/1969) delivered his epic paper, "On the speed of mental processes." Donders' paper launched the chain of events that ultimately lead to the symposium, i.e., the study of mental chronometry. Moreover, both Donders' efforts and those of latter mental chrono-
metricans have depended crucially on the temporal organization of the component processes that determine reaction time (RT). This organization, in turn, depends crucially on whether the transmission of information between component processes is discrete or continuous.

The present study continues the central theme of Donders' paper. Donders attempted to "fractionate" RT, i.e., to study the timing of the component processes that contribute to RT. Since Donders, there have been other attempts to fractionate RT, e.g., the Additive Factors Method (Sanders, 1980; Sternberg, 1969). Psychophysiological measures have also played a role in these attempts. For example, EMG onset has been used to divide the RT interval into "motor" and "premotor" reaction time (Weiss, 1965). Another example is the use of P300 latency to determine whether effects on RT reflect changes in the duration of "stimulus evaluation" or response processes (Maglieri et al., 1984; McCarthy and Donchin, 1981). The present study uses another psychophysiological measure, one associated with activation of the motor system, to subdivide the RT interval. This measure is called the Lateralized Readiness Potential (LRP).

1.1. Lateralized readiness potential

The LRP is thought to arise from activity in the precentral motor cortex (for reviews see Coles, 1989; Smid, 1993). It is recorded during choice RT tasks from electrode sites located over the left (C3') and right (C4') motor cortices (see Recording section in Methods). Let the potentials recorded at these sites at time \( t \) be denoted \( C3'(t) \) and \( C4'(t) \), and let the difference between these sites when a left- or right-handed response is signalled be denoted left hand \( [C3'(t) - C4'(t)] \) and right hand \( [C3'(t) - C4'(t)] \). Then the LRP at time \( t \) is defined as:

\[
\text{LRP}(t) = \text{left hand } [C3'(t) - C4'(t)] - \text{right hand } [C3'(t) - C4'(t)].
\]

A useful property of the LRP arises from alternative definitions of time \( (t) \). The LRP can be either stimulus- or response-locked. Stimulus-locked (S-locked) means that each point in the LRP is based on points from individual trials that follow the response signal (RS) by the same amount of time \( (t = 0 \text{ at RS onset}) \). Response-locked (R-locked) means that each point in the LRP is based on points from individual trials that precede the overt response (RT) by the same amount of time \( (t = 0 \text{ at RT}) \). The interval between the RS and S-locked LRP onset (RS-LRP interval) is related to the duration of the processes that occur before the start of the LRP, and the interval between R-locked LRP onset and RT (LRP-RT interval) is related to the duration of processes that occur after the start of the LRP. By examining which of these two intervals are affected by an experimental manipulation, it is possible to determine whether the manipulation's effects on RT occur before or after the start of the LRP.

1.2. Using S-locked and R-locked LRPs to fractionate RT effects

Several manipulations have been found to effect only the RS-LRP interval. These include manipulations of the psychological refractory period (Osman and
Moore, 1993), stimulus redundancy (Mordkoff et al., 1995), extent of mental rotation (Band and Miller, 1993), and set size in memory scanning (Ilan, 1995). Lack of an effect on the LRP–RT interval has several implications. First, it indicates that a manipulation has its entire effect on RT before LRP onset. It also indicates that the RS–LRP interval can be selectively influenced, i.e., effects on this interval need not propagate onto the LRP–RT interval. Selective effects on the RS–LRP interval could prove troublesome for some continuous models, but are easy to reconcile with models in which the pre and post LRP intervals reflect the duration of separate serial stages.

There are few, if any, published reports of relevant effects on the LRP–RT interval. By relevant, we mean explicitly measuring R-locked LRPs and satisfying two conditions that we regard as necessary for using LRPs to fractionate effects on RT: (1) The LRP must arise as part of the response measured by the RT; and (2) LRP onset must occur within the RT interval. (LRPs before the RS in response to another signal, for example, would satisfy neither condition.) Finding effects on the LRP–RT interval under these conditions would provide information both about the processes that occur at the end of the RT interval and about the particular manipulation that produced the effect. It would also aid in the interpretation of effects on RT that occur entirely before LRP onset. Clearly, such effects would be more informative if we knew that it was possible to obtain an alternative pattern of results.

The present study attempted to produce an effect on the LRP–RT interval. We reasoned that the manipulations most likely to produce such an effect would be those that influenced motor programming processes, i.e., processes that specify the anatomical or kinematic parameters of a movement or movement sequence. Our rationale was that any motor programming that occurred during the RT interval would be likely to take place just before the start of the movement. One type of manipulation thought to influence motor programming (Rosenbaum, 1980) involves presenting advance information about anatomical or kinematic parameters of the response to be signalled in a choice RT task. This manipulation is referred to as precuing.

1.3. Precuing procedure

Rosenbaum (1980) developed a procedure in which precues are used to study how the parameters of a movement are specified prior to its execution. The procedure involves: (1) a set of movements that differ with respect to several parameters (e.g., arm, direction, or extent), (2) a set of response signals, each of which signals one of the movements in a choice-RT task, and (3) a set of precues that are presented before the RS and provide advance information about parameters of the upcoming movement. Specifying the value of a parameter (e.g., forward vs. backward movement) is assumed to take time and, in the absence of advance information, to contribute to RT. Rosenbaum (1980) hypothesized that when a precue provides advance information about a movement parameter, the parameter can be specified prior to the RS, thus removing its contribution to RT.
Not everyone agrees that precues affect motor programming. Rosenbaum (1980) acknowledged that at least part of the RT effect is due to a reduction in the number of S–R alternatives and can thus be attributed to other processes. Some (e.g., Goodman and Kelso, 1980; Proctor and Reeve, 1986), however, have argued that none of the RT effect is due to the influence of precues on motor programming. Instead, they attribute all or most of the RT effects to changes in the duration of "S–R translation" processes, which select the signalled response from among the set of response alternatives. These processes are thought to specify the signalled response at a fairly abstract level, leaving the subsequent specification of its anatomical and kinematic parameters to motor-programming processes.

Finding effects of precues on the LRP–RT interval might help provide support for the hypothesis that they affect motor programming. More specifically, it would constitute the first of two steps. The remaining step would be to show that factors which influence the duration of S–R translation processes (Kornblum et al., 1990; Sanders, 1980) do not affect the duration of the LRP–RT interval. Regardless of its outcome, an experiment examining precue effects on the LRP RT interval would provide unequivocal information about the temporal locus (before or after LRP onset) of any effects observed on RT. If there is an effect on the LRP–RT interval, we will have demonstrated the possibility of effects on this interval, and will then be in a position to ask whether this finding could have been due to effects on processes besides motor programming, e.g., S–R translation.

1.4. Present experiment

The present experiment employed a precuing procedure similar to that used by Proctor and Reeve (1986). Here, the responses involved a key press with the index or middle finger on the left or right hand. Precues indicated two of the four possible response fingers or were uninformative. To minimize lateralized artifacts (from eye movements and sensory responses) that can influence LRP measurements, all stimuli and responses occurred at subjects' midlines. Stimuli consisted of vertical columns of four stars, and responses were made by depressing one of four vertically arranged buttons. Besides RT and the LRP, we will also consider some other relevant measures: electromyographic activity (EMG) and the P300.

2. Method

2.1. Subjects

Twelve undergraduate students from the University of California, San Diego Psychology Department Subject Pool were each tested individually in a single 3-hour session. Participation in the experiment fulfilled a course requirement.

2.2. Apparatus

Stimulus presentation and data acquisition were controlled by a Dell System 200 personal computer. Stimuli were presented on a Dell VGA Color Plus monitor,
and responses were made by depressing one of four vertically arranged buttons on
the response box. Approximately 135 grams of pressure was required for a
response to be registered. Psychophysiological signals were recorded using
Ag/AgCl electrodes and a Grass Model 12 Neurodata Acquisition System.

2.3. Stimuli, responses, and trial events

All stimuli consisted of four stars arranged in a vertical column and presented
at each subject's midline. At a viewing distance of about 70 cm, each star
subtended about 0.4 × 0.3 degrees of visual angle (dva), and the entire column
subtended about 2.5 × 0.3 dva. Each trial began with the presentation of four red
stars (warning signal). One half second later, some of the red stars turned yellow
(precue). One second later, one of the yellow stars turned green (RS). This final
column of stars remained on the screen for 1500 msec, vanishing at the end of the
trial. The position of the green star within the column signalled a spatially
compatible button press on one of four vertically arranged buttons directly below
the stimuli. From top to bottom, the buttons corresponded to the right middle
(RM), right index (RI), left middle (LM), and left index (LI) fingers. There were
four types of precue: hand (top two stars turned yellow, precuing RM and RI;
bottom two stars turned yellow, precuing LM and LI), finger (top and third stars
turned yellow, precuing RM and LM; second and bottom stars turned yellow,
precuing RI and LI), ambiguous (top and bottom stars turned yellow, precuing RM
and LI; two middle stars turned yellow, precuing RI and LM), and noninformative
(all stars turned yellow).

2.4. Design

All precues provided valid information about the upcoming response signal.
Each type of precue (hand, finger, ambiguous, and noninformative) could be
followed by a response signal indicating any of the four responses (RI, RM, LI,
LM), yielding 16 (4 × 4) trial types. Each block began with three practice trials,
selected randomly from the different trial types. The practice trials were followed
by 80 correct trials, 5 from each trial type, presented in a random order. Nonprac-
tice trials resulting in errors were rerun in the same block at a random location in
the sequence of remaining trials.

2.5. Procedure

Each session consisted of 2 practice and 10 experimental blocks. During the first
practice block, the experimenter observed subjects and offered feedback on their
performance. Electrodes for measuring psychophysiological activity were then
applied (see Recording section). Subjects' electroencephalographic (EEG) and
electro-oculographic (EOG) activity were displayed for them on the monitor and
the effects of eye movements on EEG recordings demonstrated. Subjects were
asked to fixate the column of stars during each trial and to avoid eye movements and blinks while it was present on the screen. Blinks and eye movements were permitted during the intertrial interval, which was indicated by the absence of the column. Next, a second practice block was administered to further familiarize subjects with the task and give them practice minimizing eye movements. During this block the experimenter monitored eye movement and offered feedback. Finally, the 10 experimental blocks were administered.

Subjects sat facing the monitor with their fingers resting comfortably on the response buttons. Each trial lasted 3 sec and was followed by an intertrial interval. The intertrial interval lasted 2 sec, plus an additional 1/2 sec when feedback was presented. When presented, trial feedback occurred immediately after the trial and appeared on the screen just below the location of the star column. Subjects were informed if they made more than one response, no response, an incorrect response, or responded too slowly (> 1 sec). Subjects were praised following an RT below their accumulated average for that trial type. After each block, feedback concerning the subject's performance on the previous block was displayed on the monitor. This consisted of mean RT for correct responses and the proportion of correct responses. Subjects were allowed to rest for as long as they wished before initiating a new block.

2.6. Recording

EEG, EMG, and EOG activity were recorded on each trial. EEG was recorded unipolarly from midline sites, Fz, Cz, and Pz (International 10/20 System; Jasper, 1958), and referenced to linked mastoids. EEG was recorded bipolarly from electrode sites C3' and C4', 4 cm to the left and right from Cz (vertex) along the interaural line. Vertical and horizontal EOG activity was recorded bipolarly from sites above and below the midpoint of the right eye and 2 cm external to the outer canthus of each eye. EMG was recorded bipolarly from the dorsal surface of each forearm, using standard extensor placements (Lippold, 1967). Signals were filtered online with a band pass (half-power cutoff) of 0.01 to 30 Hz for EEG and EOG and 0.3 to 30 Hz for EMG. All signals were digitized at 100 Hz, and the recording epoch was 3,000 msec, starting with the presentation of the warning signal.

2.7. Data reduction

Overt performance

RT was defined as the time between response signal onset and the first closure of the microswitch beneath a response button. A correct trial was defined as one on which microswitch closure occurred for the signalled button only and before the end of the trial (RT < 1.5 sec). Accuracy was defined as the number of correct trials (200 per subject per precue condition) divided by the total number of trials.

Psychophysiological waveforms

Average S- and R-locked waveforms were obtained for the LRP, horizontal EOG (HEOG), rectified EMG in the responding arm, and ERP at site Pz (where
P300 is maximal). Average waveforms were based on the waveforms from individual correct trials and were obtained for each subject in each precue condition. Each waveform was adjusted by subtracting a baseline voltage from all time points. S-locked waveforms were adjusted by subtracting the average voltage during either the first 200 msec of the recording interval (ERP at Pz) or the 200 msec just before the RS (EMG, LRP, HEOG). R-locked waveforms were adjusted by subtracting the average voltage during the interval 600–400 msec before RT.

LRPs were obtained from the bipolar recordings of the difference between electrode sites C3' and C4' according to Eq. (1), where “right” and “left” indicate the hand of the signalled finger. To evaluate the contribution of horizontal eye movements to the observed LRPs, bipolar recordings from the HEOG channel were analyzed in a manner similar to the LRP. This involved substituting the bipolar recordings from the HEOG channel for (C3' – C4') in Eq. (1).

Timing and amplitude of EMG

Onset latencies were obtained for each subject’s average S- and R-locked EMG in each precue condition. Two criterions were defined for each subject, one for their S-locked EMGs and one for their R-locked EMGs: First, the maximum amplitude was obtained for a subject’s S- or R-locked EMGs in each precue condition (after applying a 8.8 Hz low-pass filter); The maximum amplitudes were then averaged and a criterion set at 10% of the average. The onset of a given waveform (unfiltered) was defined as the point at which it began to maintain an amplitude consistently above the criterion. This required that the voltage at onset and the average voltage during the next two 50 msec windows exceed the criterion. The peak amplitude for each R-locked EMG, as well as the time at which it occurred, were also determined.

LRP onset

Onset latencies were obtained for each subject’s average S- and R-locked LRPs in three precue conditions: finger, ambiguous and noninformative. It was not possible to obtain onset latencies in the hand precue condition because the LRP was already present at the time of RS presentation. LRP onset latencies were obtained in the same manner as EMG onset latencies, but with two exceptions. First, each criterion was based on the average of the maximum amplitudes of three (rather than four) waveforms. Second, the criterion was set at 25% (rather than 10%) of the average.

P300 latency

P300 latency was obtained from recordings at site Pz that were smoothed using a 8.8 Hz (half power) low-pass filter. P300 latency was defined as the interval between the RS and the maximum positivity occurring from 300 to 800 msec after the RS.
3. Results

Results concerning overt performance, EMG activity, P300 latency, the LRP, and horizontal eye movements are each discussed in a separate subsection. Each measure described here was obtained separately for each subject. All ANOVAs are one-way, with precue type as the single factor and replications over subjects. All comparisons between means employed Tukey's Honestly Significant Difference Test. Table 1 provides a summary of all the results presented in this section. Shown here is the mean of each measure, averaged across subjects, in each precue condition.

3.1. Overt performance

Mean RT and error rate are presented graphically in the top panel of Fig. 1. Precue type had a significant effect on both RT ($F(3,33) = 77.3; p < 0.001$) and error rate ($F(3,33) = 2.88; p = 0.051$). RT was slower with noninformative precues than with hand, finger, or ambiguous precues ($p < 0.001$), but did not differ significantly between any of these latter three precue types ($p > 0.05$). Post hoc analyses did not detect a significant difference in error rate between any pair of precue types, but the largest value was obtained in the noninformative precue condition.

The bottom panel of Fig. 1 shows that the pattern of precue effects on mean RT also extended to the entire RT distribution. Shown here are the cumulative distribution functions (CDFs) for each precue type. Time is represented on the horizontal axis, and the percentage of RTs equal to or faster than a given time is shown on the vertical axis. Each CDF was obtained by Vincentizing (averaging the

<table>
<thead>
<tr>
<th>Measure</th>
<th>Precue type</th>
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<tr>
<td></td>
<td>Hand</td>
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<tr>
<td>Mean RT (msec)</td>
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<tr>
<td>Error rate (%)</td>
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<tr>
<td>R-locked</td>
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<td>Peak latency (msec)</td>
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<tr>
<td>Peak amplitude (uV)</td>
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<td>Lateralized readiness potential</td>
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<tr>
<td>Onset (msec)</td>
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<td>R-locked onset (msec)</td>
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</tr>
<tr>
<td>P300 latency (msec)</td>
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</table>
Fig. 1. Reaction times and accuracy for each precue type. The top panel shows mean reaction times (RT) and percent error (ACC). The bottom panel shows visualized cumulative distribution functions of reaction times.

$X$ values for each $Y$ value) the CDFs from individual subjects. The CDFs for hand, finger, and ambiguous precues are virtually identical. The CDF for noninformative precues is slower than the other three at all percentiles.

3.2. Electromyographic activity

The grandaverage of S-locked EMG activity for each precue type is shown in the top panel of Fig. 2. Time is displayed along the $X$ axis, and voltage is displayed along the $Y$ axis. The dashed vertical lines indicate the onset of the warning signal.

Fig. 2. Grandaverages of electromyographic activity in the responding arm for each precue type. The top panel shows the stimulus (S)-locked grandaverages. The bottom panel shows response (R)-locked grandaverages. WS = warning signal, PC = precue, RS = response signal, and RT = reaction time.
Fig. 3. Grandaverages of stimulus-locked ERPs recorded from electrode site Pz for each precue type. Note that the P300 component occurs approximately 300 msec after the presentation of the response signal. WS = warning signal, PC = precue, RS = response signal, and RT = reaction time signal.

The pattern of effects on S-locked EMG onset latency was similar to that found for RT. Precue type had a significant effect ($F(3,33) = 64.8; p < 0.001$). EMG activity began later with noninformative precues than with any of the other three precue types ($p < 0.01$), and EMG onset did not differ significantly between any of the other three precue types ($p > 0.05$).

The grandaverage of R-locked EMG activity for each precue type is shown in the bottom panel of Fig. 2. As can be seen, precue type had little effect on the R-locked EMG; The four waveforms are almost identical. This observation was evaluated statistically by examining three measures: onset latency, peak latency, and peak amplitude. Precue type had no significant effect on onset latency ($F(3,33) = 1.57; p = 0.215$). Effects on peak latency ($F(3,33) = 2.39; p = 0.09$) were marginally significant, but very small (2 msec difference between the fastest and slowest precue types). Effects on peak amplitude were not significant ($F(3,33) = 2.1; p = 0.119$), and the greatest difference observed between two precue types was small (about 2.5% the amplitude of either).

3.3. P300

Grandaverage ERPs recorded at Pz, the electrode site where P300 is largest, are shown in Fig. 3. (Note that positive is plotted down here.) The P300s to the RS are the positive deflections that peak 3-500 msec after the dashed line corresponding to RS onset. Precue type had a significant effect on P300 peak latency ($F(3,33) = 8.92; p < 0.001$). P300 peak latency did not differ significantly between hand, finger, and ambiguous precue types ($p > 0.05$). Peak latency was significantly longer ($p < 0.01$) for noninformative precues than for finger or ambiguous precues, but was 1 msec shy of significantly longer ($p < 0.05$) than for hand precues.

3.4. Lateralized readiness potentials

The grandaverage S-locked LRP for each precue type is shown in the top panel of Fig. 4. As can be seen, an LRP during the foreperiod occurred for the hand
precues. A planned test found the area under this LRP during the 500 msec preceding the response signal to be significantly greater than zero \( t(11) = 22.5; p(\text{one-tailed}) < 0.001 \). Precue type had a significant effect on LRP latency \( F(2,22) = 15.77; p < 0.001 \). LRP latency was significantly longer with noninformative precues than with either finger \( p < 0.01 \) or ambiguous precues \( p < 0.01 \), but did not differ significantly between these latter two precue types \( p > 0.05 \).

The pattern of precue effects on R-locked LRP latency was similar to that found for S-locked LRP latency. Grandaverage R-locked LRPs for finger, ambiguous, and noninformative precue types are shown in the bottom panel of Fig. 4. Precue type had a significant effect on R-locked LRP latency \( F(2,22) = 14.9; p < 0.001 \). The interval between LRP onset and RT was significantly longer for noninformative precues than for either finger \( p < 0.01 \) or ambiguous \( p < 0.01 \) precues, but did not differ significantly between the latter two precue types \( p > 0.05 \).

3.5. Effects of horizontal eye movements on LRP recordings

HEOG recordings are shown at the bottom of each panel in Fig. 4. Each HEOG waveform was recorded in the same precue condition as one of the LRPs above. HEOG was analyzed in exactly the same way as the LRP (see Data Reduction section), but is displayed at a scale 25% that of the LRP. This scale equals a conservative estimate (high side) of the propagation coefficient relating HEOG recorded from the outer canthi (eyes) and HEOG recorded from central electrode sites (Hillyard and Galambos, 1970). In other words, the HEOG is scaled
4. Discussion

This study examined the effects of precuing on RT and several psychophysiological measures, in particular the LRP. The primary goal was to help provide a foundation for using LRPs to fractionate experimental effects on RT. Another goal was to help identify the processes responsible for precue effects on RT. In the following discussion, we first consider the implications of our findings for the locus of precue effects on RT. We then turn to the interpretation of effects on the LRP-RT interval and conclude by considering the possibility of using this interval to study "motoric" components of RT in isolation.

4.1. The locus of precuing effects on RT

The same pattern was found for all latency measures timed with respect to the RS, including RT: Each was shorter with informative than noninformative precues, but did not differ between informative precues. Differential effects on RT of precuing different response parameters has been interpreted as evidence that the RT effects involve motor programming processes (Rosenbaum, 1980). The absence of such differences, however, does not imply that motor-programming processes were not involved. Nevertheless, the precue effect on P300 latency does suggest that at least part of the effect on RT was due to changes in the duration of "stimulus evaluation" processes. Changes in the duration of stimulus evaluation might also account for the S-locked LRP and S-locked EMG findings, since slower stimulus evaluation could delay the start of response-related processes.

Precuing had little or no effect on the dynamics (amplitude profile over time) of muscle activity at the end of the RT interval. The R-locked EMG grand averages were virtually identical in all precue conditions. We picked several measures – onset, peak latency, and peak amplitude – in order to perform statistics based on the waveforms from individual subjects. When averaged across subjects, these measures, like the grand averages, were virtually identical. While this rules out a precue effect on the very latest portion of the RT, it is not incompatible with effects on motor-programming. One might expect that specification of the parameters involved in selecting response finger would occur before EMG onset. With other response sets and precued parameters (e.g., force), there might very well be precue effects after the start of EMG.

As anticipated, an LRP occurred during the foreperiod when the precue provided information about response hand. This replicates previous findings (e.g., De Jong et al., 1988; Ulrich et al., 1993,1994) and shows that the hand precues activated motor cortex. The similar RT distributions for all informative precues.
suggests that these precues produced similar effects, including activation of motor cortex. If so, one would still expect the absence of a foreperiod LRP when precuing fingers on opposite hands, since both hemispheres would be activated. Does motor system activation on opposite hands implicate motor programming in the RT effects? While suggestive, such evidence is not entirely conclusive. It remains possible that the RT effects were due entirely to processes carried out by other portions of the nervous system.

In a sense, the presence vs. absence of a foreperiod LRP is an effect on the LRP–RT interval, but not the kind we were looking for. Here, LRP onset does not provide a temporal landmark within the RT interval, since it is already present before the RS. What we sought – and found – were effects of other precue types on the LRP–RT interval when hand information was not precued. Precues indicating two fingers on different hands (either homologous and nonhomologous) produced shorter LRP–RT intervals than noninformative precues. This indicates that on at least some trials the interval between LRP onset and RT was shortened by advance information about the upcoming response. It would now be interesting to see if manipulations believed to affect processes besides motor programming, e.g., S–R translation, also produce effects on the LRP–RT interval. Each negative finding would rule out a process other than motor programming as responsible for precue effects on the LRP–RT interval.

4.2. Interpreting effects on the LRP–RT interval

An effect on the R-locked LRP–RT interval provides information about the temporal locus of an effect on RT: It occurs after LRP onset on at least some portion of the trials. Can we use this information about the temporal locus of an effect to draw inferences about the its functional locus, i.e., the identity of the affected cognitive processes? Like other attempts to fractionate RT, the interpretation of effects on the LRP–RT interval depends on the temporal arrangement of the component processes that determine RT. Not coincidentally, the temporal arrangement of these component processes depends crucially on whether they transmit information continuously or in discrete quanta (e.g., Miller, 1988; Meyer et al., 1985).

Let's consider the implications of three such arrangements, or architectures, for the interpretation of effects on the LRP–RT interval. These architectures are illustrated in Fig. 5. To simplify matters, the component processes in each are characterized only as motoric or nonmotoric. Motoric processes are those involved in motor programming or in implementing the parameters selected by programming processes. Nonmotoric processes are all the other processes (e.g., perceptual or S–R translation). The top panel shows an arrangement in which RT can be divided into at least two serial stages. The earlier stage contains only nonmotoric processes, and the later stage contains only motoric processes. The LRP first arises during the motoric stage when one hand becomes more prepared than the other. Here, of course, any effect on the LRP–RT interval can be attributed solely to changes in the duration of motoric processes.
Fig. 5. Alternative arrangements of motoric and nonmotoric RT components. The top panel shows a single nonmotoric stage followed by a single motoric stage. Here the LRP–RT interval reflects only the duration of motoric processes. The other two panels show arrangements in which the LRP–RT interval reflects the duration of nonmotoric processes. In the middle panel, nonmotoric processes occur in parallel with motoric processes. In the bottom panel, a motoric stage is followed by a nonmotoric stage. M = motoric processes, NM = nonmotoric processes, RS = response signal, LRP = lateralized readiness potential, and RT = reaction time.

The middle panel of Fig. 5 shows an arrangement involving temporal overlap between motoric and nonmotoric processes. This situation could arise if some motoric processes were guided by preliminary output from nonmotoric processes, while other motoric processes began only after all nonmotoric processes were complete. For example, suppose that in the current experiment the RS was identified in two steps: (1) Determine whether the green star occurs in the top or bottom half of the vertical array, then (2) determine which of the two remaining positions it occurs in. Hand preparation (and the LRP) could begin as soon as step 1 was complete, while further preparation of the responding finger would have to wait until both steps were complete. Here, effects on the LRP–RT interval could be caused by changes in duration of the latter set of nonmotoric processes, i.e., if the finger or ambiguous precues influenced step 2 of RS identification.

Nonmotoric effects on the LRP–RT interval could also occur in the absence of temporal overlap between motoric and nonmotoric RT components. The bottom panel of Fig. 5 shows a series of four stages, two motoric and two nonmotoric. Again, suppose that identification of the RS involved the two steps mentioned above. The earlier nonmotoric stage could correspond to the first step, the earlier motoric stage could correspond to preparation of the response hand, the later nonmotoric stage could correspond to the second step of RS identification, and the later motoric stage could correspond to further preparation of the responding finger. As in the middle panel, the LRP–RT interval would then reflect the duration of the second step of RS identification.

4.3. Using the LRP–RT interval to isolate "motoric" processes

Which of the above architectures, if any, is true? They may all be, each providing an accurate representation of RT under a different set of circumstances.
One clear lesson from research on discrete vs. continuous processes is that the temporal arrangement of processes during RT depends on the specific details of an experiment, e.g., the task (Meyer et al., 1988; Meyer et al., 1985), the stimuli (Miller and Hackley, 1992; Ridderinkhof et al., 1995), or subjects' strategies (De Jong et al., 1988; Smid and Mulder, 1995). The implications for the interpretation of effects on the LRP-RT interval are: (1) that effects on the LRP-RT interval may reflect different processes under different conditions, and (2) that it may be possible to select an architecture in which effects on the LRP-RT interval are especially interesting.

Perhaps, a choice-RT task could be arranged such that the LRP-RT interval contained only motoric processes (Fig. 5, top panel). This could be confirmed by manipulating a set of factors thought to affect a wide range of nonmotoric processes, but not motoric processes. Many such factors have been identified using the Additive Factors Method (Sanders, 1980; Sternberg, 1969). If these factors all affected RT, but not the LRP-RT interval, it would be reasonable to conclude that the LRP-RT interval was uninfluenced by the duration of nonmotoric processes. Effects of other factors on the LRP-RT interval could then be attributed solely to changes in the duration of motoric processes.

Were this possible, the LRP-RT interval could be used to study motoric processes in isolation and would have many applications beyond the precuing paradigm. For example, it could help confirm previous conclusions about the motoric effects of other experimental manipulations, such as temporal uncertainty of the RS (Sanders, 1980). It might also help eliminate the contribution of nonmotoric processes in other paradigms used to study motoric processes, such as those involving manipulations of response complexity (Klapp, 1978; Sternberg et al., 1978) or response-response compatibility (Heuer, 1986; Kornblum, 1965). More generally, the functional properties of motoric processes might be specified by identifying which factors affect the duration of the LRP-RT interval and which don’t (Sanders, 1980; Sternberg, 1969).

4.4. Conclusions

Precuing affected the LRP-RT interval. This finding enhances the “news value” of previous studies in which the entire effect on RT preceded LRP onset, and it may help identify the processes responsible for precue effects on RT. Most importantly, it suggests that the LRP-RT interval may provide a window on the duration of processes occurring at the end of the RT interval, especially motoric processes. We predict that the LRP-RT interval of the R-locked LRP will prove to be a useful tool for fractionating effects on RT and for the chronometric study of motoric processes.

References


