The lateralized readiness potential and response kinetics in response-time tasks

J. TOBY MORDKOFF AND MARC GROSJEAN
Department of Psychology, The Pennsylvania State University, University Park, USA

Abstract

Previous studies have found that the magnitude of the lateralized readiness potential (LRP) at the time of response initiation is constant across spontaneous variations in response time in both cued and uncued, speeded tasks. Other studies have found that the LRP is also unaffected by instructed changes in peak response force and time to peak force in cued, self-paced tasks, but that the LRP is sensitive to instructed changes in force gain rate in uncued, self-paced tasks. The present study examined the LRP in an uncued, speeded task as a function of response time and several measures of response kinetics. The magnitude of the LRP at the time of electromyographic onset was constant across spontaneous variations in all measures. The peak of the contingent negative variation did vary as a function of peak response force and integrated force to peak, but not response time. These findings support the idea that the LRP in speeded tasks is a selective, on-line index of the preparation associated with using a particular hand, and is not an index of the elements of motor programming that determine subsequent response kinetics.

Descriptors: Lateralized readiness potential, Response kinetics, Response force, Response time, Spontaneous variations

Prior to 1980, almost all of the work in experimental cognitive psychology was performed using only two dependent measures: response accuracy and response time (RT; defined as the interval between reaction-stimulus onset and the initiation of a response). Under the typical set of instructions given to participants (i.e., "respond as quickly as possible while making very few errors"), the value of RT provides the total amount of time that was required to perform the task, whereas dichotomous accuracy indicates whether the task was performed correctly. In the last 20 years, paralleling an explosive growth in psychophysiology, many researchers who are interested in cognitive processes have started to use event-related brain potentials (ERPs) to make some of their inferences. This broadening of dependent measures is probably due to the fact that ERPs can often provide a series of on-line measures of the various, embedded, mental processes that are being used to perform the task (see, e.g., Coles, 1989; Kutas & Van Petten, 1994). Most important: when used carefully, ERPs are sometimes capable of discriminating between alternative, competing cognitive models that make identical predictions for mean RT and accuracy (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Hillyard & Münte, 1984; Miller & Hackley, 1992; Mordkoff, Miller, & Roch, 1996). In other words, in some cases the use of ERPs has been critical to advances in our understanding of mental processes.

For ERPs to be used with confidence, however, the relationship between a given waveform component and one or more cognitive processes must be known in advance. The specific relationship between an ERP component and a cognitive process is referred to as an indexing function (cf. linking proposition; Teller, 1984). Examples of indexing functions that have been used to address important questions include the magnification of the P1 component as a measure of spatial attention (e.g., Hillyard & Münte, 1984; Hopfinger & Mangun, 1998), the latency of the P300 component as a measure of the time required by stimulus evaluation (e.g., Gratton et al., 1990; but see, also, Verleger, 1997), the magnitude of the P300 as an index of stimulus expectancy (e.g., Van Petten et al., 1990), the magnitude of the N2pc component as a measure of attentional focusing (e.g., Luck & Hillyard, 1994), and the magnitude and timing of the N400 component as a measure of various linguistic processes (e.g., Van Petten & Kutas, 1991). The present paper concerns one of the most popular ERP components with important features of the most simple and powerful indexing functions: the magnitude of the lateralized readiness potential (LRP) as an online index of response preparation (e.g., De Jong, Wierda, Mulder, & Mulder, 1988; Leuthold, Sommer, & Ulrich, 1996; Miller & Hackley, 1992; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Ulrich, Leuthold, & Sommer, 1998).

The Lateralized Readiness Potential

Prior to the initiation of almost any voluntary movement, a negative voltage potential can be observed at a variety of sites on the scalp. However, prior to a right-hand movement, a particularly large negative potential is found over the left precentral gyrus and, conversely, prior to a left-hand movement, a large negative potential is found over the right precentral gyrus (see, e.g., Kutas & Donchin, 1980). When this lateralized difference is measured (using
electrodes placed near the 10-20 locations of C3 and C4), the contralateral negativity is referred to as the lateralized readiness potential (LRP; also known as the corrected motor asymmetry). More formally, the LRP at any given point in time can be defined as

\[ \text{LRP}(t) = [C3'(t)\text{LH} - C4'(t)\text{LH}] - [C3'(t)\text{RH} - C4'(t)\text{RH}], \]

where \( C3'\) (\( \text{LH} \)), for example, represents the voltage observed at a location slightly anterior and superior to the 10-20 location C3 at time \( t \) on a trial that requires a left-hand response. The reason for using a double subtraction (across trials involving different hands) is to remove any lateralized potentials that are not associated with the actual response (for complete details and some discussion of the neural substrates of the LRP, see, e.g., De Jong et al., 1988; Miller & Hackley, 1992; Osman et al., 1992). Note that a variety of specific formulae for calculating the LRP have been used (some arranged to produce negative values; others dividing the present value by two), but all are functionally identical to the formula used here. Note, also, that only the LRP that are observed prior to response production are usually considered, in order to avoid contamination from reafferent (tactile) feedback that follows actual movement.

As stated above, it is widely assumed that the LRP provides an on-line measure of response preparation or response activation (for a review, see, e.g., Coles, 1989; Miller & Hackley, 1992). Some of the strongest evidence for this indexing function comes from a pattern of results that obeys what we shall refer to as “Gratton’s Rule” (after Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). In particular, in speeded tasks, the LRP has been shown to have a (relatively) fixed magnitude at the moment of overt response initiation, regardless of response speed, accuracy, or experimental condition. If the LRP is truly an on-line index of response preparation, it must be a measure that is constant across all subsets of the data, where the subsets are created by dividing a large set of data into bins or quantiles of various speeds. The goal of the present study was to conduct a new test of Gratton’s Rule, using data that have been response-locked to EMG onset (cf. Hackley & Miller, 1995). Verification of the rule under these particular conditions would increase our confidence that the LRP is a true on-line index of response preparation.

Response Kinetics

Although initially treated separately from research using the LRP, there has also been a recent increase in the use of measures of overt behavior that go beyond the traditional measures of RT and accuracy (see, e.g., Abrams & Balota, 1991, for a rationale). In particular, several studies of speeded performance have examined task-irrelevant variations in response kinetics as ancillary measures of motor processing (e.g., Giray & Ulrich, 1993; Mordkoff et al.,...
force

1996; Ulrich & Mattes, 1996). This approach capitalizes on the fact that participants often “overshoot” the required amount of force by as much as 1500%, and that the relative variability of peak force (PF) is often as high as that of RT. As a concrete example of the logic that has been used, Giray and Ulrich suggested that the higher levels of PF that are observed when participants are presented with multiple targets (as opposed to only one target) provide evidence that “coactivation” may occur within the motor component (cf. Mordkoff et al., 1996). Other work has attempted to discriminate between discrete and continuous models of information transmission by examining PF, as well as integrated force (i.e., force impulse size), the rate of force development (i.e., force gain rate), the duration of force production, and several measures of the shape of the force-time function (e.g., Ulrich, Rinkenauer, & Miller, 1998).

As might be expected, several of the experimental manipulations that are known to reduce mean RT also have the effect of increasing mean PF (e.g., stimulus intensity; Ulrich, Rinkenauer, et al., 1998; number of stimuli in simple-RT tasks, Giray & Ulrich, 1993; number of targets in some go/no-go tasks, Mordkoff et al., 1996). In other words, there is often a strong negative correlation (across conditions) between mean RT and mean PF. What might seem somewhat surprising is that the trial-by-trial correlation between RT and PF has always been found to be very near zero (e.g., Giray & Ulrich, 1993; Mordkoff et al., 1996, Ulrich, Rinkenauer, et al., 1998). This suggests that the analysis of response kinetics, including the measurement of PF, can provide independent information concerning motor processing from that which is given by traditional measures, such as RT.

Response Kinetics and the LRP

It is important to note that the analyses that produce evidence in favor of Gratton’s Rule and that demonstrate a null correlation between RT and PF are in many ways quite similar. Most important, both concern the spontaneous variations in performance that are observed within an experimental condition. In the former case, stochastic variation in RT is used to divide the data into subsets, such that the LRP can be compared across different speeds of responding; in the latter case, stochastic variation in RT is compared with stochastic variation in PF on a trial-by-trial basis. If it were not for the fact that the calculation of the LRP requires that many trials be averaged together (because of the low signal-to-noise ratio of ERP signals), the two analyses would be nearly identical.

In the existing literature, however, the studies that have explored any possible links between the LRP and response kinetics have not capitalized on spontaneous variations in overt performance. Instead, these studies have used instructions that require participants to produce responses with different levels of PF, often at various lags between force onset and peak force (i.e., time to peak force, TTP). The most relevant study, that of Sommer et al. (1994), found no evidence that the magnitude of the LRP at the time of response initiation is affected by either instructed PF or TTP. In particular, the response-locked LRP within a window from 200 to 100 ms prior to response initiation were approximately equal across both low and high levels of PF (instructed PF was either 10 or 50% of the participant’s maximum voluntary force; MVF) at both short and long lags between force onset and peak force (instructed TTP was either 100 or 200 ms). This supports the idea that the LRP is a selective index of the preparation associated with using a particular hand, and is not an index of the processes that determine response kinetics. This, in turn, implies that researchers using the LRP to address questions unrelated to the specifics of force production need not be concerned if different experimental conditions happen to produce different levels of mean PF.

Before continuing, however, it should be noted that some researchers have argued that the underlying control parameters for brief, isometric responses are not PF and TTP, but are the rate of force development (i.e., force gain rate; FGR) and the duration of force production (which is highly related to TTP; see, e.g., Ivry, 1986; Newell & Carlton, 1988; Ulrich & Wing, 1991). Thus, it is useful to reanalyze the results from Sommer et al. (1994), because this study can also be viewed as requiring four different levels of instructed FGR (because both PF and TTP were specified, but happen to produce four different ratios). This allows for a test of a possible relationship between the LRP and FGR. The four values of FGR from Sommer et al. were 50, 100, 250, and 500 %MVF/s; the four observed mean magnitudes of the LRP in the interval just preceding response initiation were 1.74, 1.66, 2.04, and 1.71 μV, respectively. These data exhibit a linear correlation of only .09. Thus, even when FGR is assumed to be one of the control parameters of isometric force production, the study of Sommer et al. (1994) provides no evidence of a clear relationship between the LRP and response kinetics.

In contrast, some very recent research using a different task has found a very different pattern of results (Ray, Slobounov, Mordkoff, Johnston, & Simon, 2000). Before reviewing this study, it is important to make clear the distinctions between the various types of task that have been used to examine the LRP. The first type of task requires “uncued/self-paced” responding (see, e.g., Kutas & Donchin, 1980), where participants are told which response to make long before the trial begins (hence the label “uncued”) and are allowed to produce the response without time constraints (ergo, “self-paced”). A second type of task is “cued/self-paced” (see, e.g., Sommer et al., 1994). This is similar to uncued/self-paced, but provides a limited window within which the response must be made. Cued/self-paced tasks also often involve two separate stimuli on each trial: a response cue that indicates which response should be made and a go stimulus that marks the beginning of the response window. A third type of task, “speeded” (see, e.g., Hackley & Miller, 1995), also begins the trial with a cue that tells the subject which response to make, but now the participants are asked to respond as quickly as possible when they detect the go stimulus. As was also true for cued/self-paced tasks, the interval between the response cue and the go stimulus may be manipulated as a way of varying the amount of time that participants have to prepare to respond. However, in contrast to cued/self-paced tasks, speeded tasks usually include a number of “catch” trials (where the go stimulus is replaced by a no-go stimulus and the participant must not respond) in order to prevent stimulus anticipation or to allow one to study other aspects of information processing (see, e.g., Mordkoff et al., 1996). Finally, a fourth type of task is the classic and basic “response-time” task (e.g., Coles et al., 1985), where participants are not told which response to make in advance. Instead, under response-time tasks, the first stimulus only acts as a warning that the trial has begun (i.e., it only provides temporal information) and the second stimulus both tells the participant which response to make and also indicates that the response should be made immediately.

The study of Sommer et al. (1994), which found no relationship between the LRP and response kinetics, used a cued/self-paced task under which participants were given 1,000 ms to prepare the response (i.e., the stimulus onset asynchrony between the response
cue and the go stimulus was 1,000 ms) and were also given a 1,200-ms window in which to initiate their response. In contrast, the study of Ray et al. (2000) used an uncued/self-paced task under which participants had known which response to make for as much as 10 s and were allowed to respond at any time that they wished. Furthermore, Ray et al. asked their participants to produce isometric responses of relatively long durations (between 1,125 and 4,500 ms) with very shallow rates of growth (instructed FGR was either 14.4 or 31.8 %MVF0) and provided visual, online feedback while the responses were being made. Under these conditions, Ray et al. observed a strong positive relationship between the magnitude of the LRP and instructed FGR.

In summary, in uncued/self-paced tasks, there is a strong relationship between the LRP and at least one measure of response kinetics (Ray et al., 2000). In cued/self-paced tasks, there is no relationship between the LRP and either PF or TTP (Sommer et al., 1994). To our knowledge, no study has examined any possible relationship between the LRP and response kinetics in speeded tasks. Because of the prevalence of these tasks in the literature on information processing and motor control, the present study was designed to fill in this gap. Furthermore, because of the importance of Gratton’s Rule to the indexing function for the LRP (see above), the present test for a relationship between the LRP and response kinetics was done by examining the spontaneous variations in response kinetics (as assessed in four different ways), instead of using instructions.

Method

Participants

Three men and three women (age range: 19–28 years) participated in a single session that lasted between 120 and 150 minutes. All reported normal or corrected-to-normal vision with no color deficits, and none had participated in a similar experiment. Each was paid $15 (U.S.) or given partial course credit for their participation.

Experimental Task

The task required subjects to discriminate between two different colors and make speeded, two-alternative, forced-choice responses. To maximize the number of observations per condition, the only manipulation concerned the presented color (green vs. purple), which specified the required response (left vs. right). Response accuracy was stressed over speed, but both were stated as being important. The only instructions regarding response kinetics and motor control mentioned that a certain minimum amount of force was required to register a response and that responses should be brief flexes of the index fingers without the additional involvement of any other muscle group (such as those related to the wrist). Consistent with this, the participants hands and wrists were strapped to the response device, such that only their fingers could move.

Design and Procedure

At all times during which written feedback was not being given, a white square box (0.97" in diameter) was presented at the center of the video screen. Each individual trial began with the appearance of a white fixation cross (0.56" square) at the center of the box. Simultaneously with fixation onset, a very brief, high tone (25 ms, 1000 Hz) was played. These two events acted as the warning stimulus. After a delay of 500 ms, the reaction stimulus replaced the fixation cross and remained visible for 1,000 ms. The reaction stimulus was created by filling in the white box with either green or purple (4-bit palette codes: 10 and 13). Half of the participants were instructed to make a left-hand response to the color green and a right-hand response to purple; the remaining participants were given the opposite mapping. During the first block (which was explicitly labeled as practice), a brief, low tone (50 ms, 500 Hz) was played when the participant produced sufficient force to register a response. After the first block, the only trial-by-trial feedback was a written message that followed an error.

The experiment consisted of 37 blocks of 12 critical trials. In contrast to the instructions, the first three blocks of trials were practice and were excluded from the analysis. The critical trials in each block were evenly divided between left- and right-hand responses. Each block also included two randomly selected “warm-up” trials (at the beginning) that were excluded from the analysis. Each error was followed by a randomly selected “recovery” trial that was also excluded. From the participants’ point of view, therefore, each block consisted of approximately 15 trials that unpredictably alternated between left- and right-hand responses. At the end of each block, the participants were given a break (at least 7 s long) and were also provided with a written summary of their performance (mean RT and accuracy).

Force Recording

Response force was measured using custom-made levers mounted on piezo-electric transducers. The conditions were near-isometric in that a force of approximately 1,000 cN bent the levers by only 2 mm. The resolution of the system is slightly below 2 cN. The values of force were digitized at a frequency of 500 Hz, starting 100 ms before the onset of fixation (to get a baseline reading) and extending until the removal of the reaction signal. The criterion value of force required to register a response was 102 cN, which is a little more than the “weight” of 100 grams at sea level.

Electrophysiological Recording

EEG signals were recorded from seven scalp sites, but the present analysis only concerns the data from C3’, Cz, C4’, and Pz. These four electrodes were all referenced to the left ear. Locations C3’ and C4’ were approximately 1 cm anterior and superior to the 10-20 locations of C3 and C4, respectively (see Jasper, 1958). Vertical EOG was recorded using a bipolar pair above and below the right eye. Horizontal EOG was recorded in an analogous manner to C3’ and C4’, using electrodes placed approximately 2 cm lateral to the outer canthi, both referenced to the left ear. EMG was recorded using bipolar pairs placed over (and in parallel to) the index-finger flexor muscles (flexor digitorum profundus) on the lower surface of the forearms. Impedance was always less than 5 kΩ for all electrodes.

The amplifier band-pass filters were set to 0.01–100 Hz for EEG and hEOG channels, 0.3–100 Hz for vEOG, and 0.1–100 Hz for EMG. All signals were digitized at a frequency of 250 Hz. The recording epoch began with a 200-ms baseline (starting 200 ms before the onset of fixation) and extended for 1,700 ms (ending when the reaction stimulus was removed). Off-line, the EEG and EOG signals were smoothed using one pass through a 24-ms (five-point) boxcar filter. The EMG signals were first high-pass filtered at 40 Hz, rectified, and then smoothed using one pass through the same boxcar filter.

Artifact Detection and Removal

Prior to the analysis, the vEOG trace from each trial was examined by two, independent raters. If either rater scored the trial as including a blink (intrarater reliability = .99), then the trial was discarded. Across the six participants, a mean of 10.9% of the trials
between C3 and C4 were remaining shifts in vEOG using the standard, regression-based method (see, e.g., Miller, Gratton, & Yee, 1988). Similarly, the difference between C3’ and C4’ was corrected for hEOG using the analogous difference between the two canthus electrodes.

In a separate step, the onset of EMG activity was estimated using the “Catch-21” method (see Mordkoff & Gianaros, 2000). This method can (in theory) be applied to any unimodal waveform. It estimates onset by fitting two intersecting lines to the data. One line remains flat at the height of the baseline; the other line rises to the time and the height of the peak. Least-squares fitting is used to select the best “break-point” between the two lines (see, also, Schwarzenau, Falkenstein, Hoorman, & Holhsbein, 1998). The “break-point” is the estimated onset. This method succeeded in identifying an onset within 150 ms prior to criterion force on 98.8% of the trials (range: 95.7–100%). The mean delay between EMG onset and force onset (see below) on acceptable trials was 17.0 ms (which is consistent with precise measurements of electromechanical delay; see, e.g., Corcos, Gottlieb, Latash, Almeida, & Agarwal, 1992). This finding makes the possibility of EMG differences prior to the identified onset of the response much less likely.

Finally, the force data from each trial were checked (by algorithm) for truncated waveforms (i.e., force-time functions that had not come to a peak at least 50 ms before the end of the recording epoch). This was necessary because several of the planned analyses require an accurate measure of the time and the height of the peak of response force. A mean of 0.6% of the trials (range: 0–3.0%) were lost to truncation. The remaining trials were scored for the time of force onset (again using the Catch-21 method), as well as peak force, force gain rate (here defined as the mean slope of the force-time function between the 25th and 75th percentiles during the rising portion of the curve), time to peak force (i.e., the lag between force onset and peak force), and integrated force to peak (i.e., the area under the force-time function between force onset and the peak).

Method of Analysis
The same set of analyses was repeated five times, using five different methods of dividing the data. In particular, the data were divided into three, equal-N subsets (i.e., quantiles) in terms of response time (RT), peak force (PF), time to peak force (TTP), force gain rate (FGR), and integrated force to peak (IFTP). In each case, the data from the two hands were ranked and divided separately (to avoid any overall speed or force differences between the hands) and then recombined to create participant-average waveforms for the “best,” “middle,” and “worst” thirds of the data.

Within each of the three subsets of data (for each of the five sets of analyses), two electrophysiological waveforms were calculated for each participant. The first was the response-locked LRP, where the moment of EMG onset was used as the time-locking event. From this waveform, the magnitude of the LRP at the time of EMG onset was calculated. This was assessed by taking the mean of the LRP within a 52-ms window that was centered on EMG onset. A comparatively small window was used because the theoretical question concerned the magnitude of the LRP at the moment of response initiation (cf. Ray et al., 2000; Sommer et al., 1994) and also to avoid any reafferent potentials. The second average waveform was the reaction-stimulus-locked, mid-line, centroparietal waveform, defined as the mean of the Cz and Pz waveforms. From this, the magnitude of the contingent negative variation (CNV; for an introduction and review, see, e.g., Rockstroh, Elbert, Canavan, Lutzenberger, & Birbaumer, 1989) was calculated as the peak (negative) amplitude within 200 ms of reaction-stimulus onset. A second measure taken from the midline waveform was the peak magnitude of the P300 component, defined as the highest (positive) amplitude between 300 and 600 ms after reaction-stimulus onset. The final measure was the latency of the P300 component, defined as the first point in time (relative to reaction-stimulus onset) at which the midline waveform achieved 75% of its maximum (positive) height.

All of the main analyses were performed by one-way, repeated-measures ANOVAs with alpha set at .05. It was planned a priori to correct for violations of the sphericity assumption using the Huynh-Feldt epsilon; however, in no case where a significant main effect was observed was Mauchly’s Test significant (all p > .25), so no corrections were ever necessary. Because of the large observed correlations between several measures of response kinetics (see below), all of the analyses were repeated using a pooled error term, but these produced the same results and are, therefore, not reported. Post hoc tests, when justified by a significant main effect in a previous ANOVA, were always two-tailed (paired) t tests with alpha again set at .05. Similarly, all tests for a significant linear correlation were two-tailed tests with alpha set at .05.

### Results

#### Descriptive Statistics

The participants were very accurate, with a mean error rate of 2.1% (range: 1.2–3.0%) and an even division of errors across the two hands. Because of their rarity, no further analyses of these data were conducted. The grand means (and standard errors) for the five overt measures within each of the three subsets are given in Table 1. Additional details on the temporal dynamics of force production are provided by Figure 2, which displays the grand-average, response-

<table>
<thead>
<tr>
<th>Division measure</th>
<th>Best third</th>
<th>Middle third</th>
<th>Worst third</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>285 ± 14 ms</td>
<td>349 ± 22 ms</td>
<td>431 ± 37 ms</td>
</tr>
<tr>
<td>Peak force</td>
<td>1,505 ± 341 cN</td>
<td>1,206 ± 309 cN</td>
<td>888 ± 265 cN</td>
</tr>
<tr>
<td>Time to peak force</td>
<td>119 ± 12 ms</td>
<td>138 ± 15 ms</td>
<td>165 ± 21 ms</td>
</tr>
<tr>
<td>Force gain rate</td>
<td>16.2 ± 3.1 cN/s</td>
<td>12.4 ± 2.5 cN/s</td>
<td>8.7 ± 1.8 cN/s</td>
</tr>
<tr>
<td>Integrated force to peak</td>
<td>251 ± 86 cN·s</td>
<td>171 ± 61 cN·s</td>
<td>110 ± 46 cN·s</td>
</tr>
</tbody>
</table>
force waveforms for each of the three subsets from each of the five analyses. As can be seen, the participants overshot the required amount of response force (102 cN) by a very wide margin, while all measures of response kinetics showed considerable within-subject variability (as indicated by the separation between the best and worst subsets). An analysis of the trial-by-trial, within-subject correlations between all pairs of the five measures (see Table 2) revealed the typical, weakly negative and unreliable relationships between RT and PF and between RT and IFTP, as well as the typical, strongly positive and significant relationship between PF and IFTP (see, e.g., Giray & Ulrich, 1993; Mordkoff et al., 1996). The one interesting new result observed here was that spontaneous variations in TTP and FGR are uncorrelated; this particular comparison has never before been reported (even though it is consistent with current, explicit models of isometric force control; e.g., Ulrich & Wing, 1991).

**Table 2. Mean Within-subject Correlation Coefficients between Overt Dependent Measures**

<table>
<thead>
<tr>
<th></th>
<th>RT</th>
<th>PF</th>
<th>TTP</th>
<th>FGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time (RT)</td>
<td>-0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak force (PF)</td>
<td></td>
<td>0.39*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to peak force (TTP)</td>
<td>0.08</td>
<td>0.84*</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Force gain rate (FGR)</td>
<td>-0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated force to peak (IFTP)</td>
<td>-0.07</td>
<td>0.95*</td>
<td>0.68*</td>
<td>0.65*</td>
</tr>
</tbody>
</table>

*Note: * indicates significant at $\alpha = .05$

**LRP Magnitude at EMG Onset**

As can be seen in Figure 3, for all five analyses (i.e., regardless of how the data were divided), the response-locked LRP s were always roughly identical across the three subsets. Most important, the mean of the LRP at the time of EMG onset did not differ across subsets in any of the analyses (see Table 3). This observation was verified by the ANOVAs, none of which produced a significant effect of data subset, all $F(2,10) \leq 1.57$. In the case of RT, this null effect was statistically significant, $F(2,10) = 3.82$, $p = .05$, with slow being lower than medium ($t(10) = 2.11$, $p = .05$); there was no significant difference for fast ($t(10) = 1.23$, $p = .25$).
finding is an extension of the evidence in favor of Gratton’s Rule to an analysis involving LRPs that have been time-locked to EMG onset (cf. Gratton et al., 1988; Hackley & Miller, 1995). The present results also go farther by showing that a similar set of “rules” may apply to all measures of response kinetics, as well.

Midline Components
In contrast to the consistent null results concerning the LRP, as can be seen in Figure 4, there appeared to be a relationship between the peak of the CNV near the time of stimulus onset and several measures of response kinetics. As also shown in Table 4, for PF, FGR, and IFTP, the best subset always showed the most negative peak amplitude. Most of this pattern was confirmed by the ANOVAs, where the effect of subset was significant for PF and IFTP, \( F(2,10) = 5.47 \) and \( 4.62 \), respectively, all others \( F(2,10) \leq 1.12 \). For both PF and IFTP, post hoc analyses found significant differences between the best subset and each of the other two subsets; the middle and worst subsets did not differ in either analysis.

Also shown in Figure 4 are the centroparietal P300 components, which appear to differ only when the data are divided in terms of RT. As shown in Tables 5a and 5b, the P300 began sooner for the fast subset and had a smaller peak for the slow subset. This was confirmed by the ANOVAs, which only found effects on the peak magnitude and the latency of the P300 in the RT analysis, \( F(2,10) = 5.03 \) and 10.34, respectively, all other \( F(2,10) \leq 2.14 \). Pair-wise comparisons of the mean peak magnitudes found significant differences between the slow subset and each of the other two; the fast and medium subsets did not differ. Pair-wise comparisons of the mean latencies found significant differences between the fast subset and each of the other two; the medium and slow subsets did not differ.

Stimulus-locked LRP Onset
Because of the importance of the consistent null results that were observed for the LRP as a function of response kinetics, an additional set of (unplanned) analyses was also conducted. This test concerns the data that are shown in Figure 1, which are the reaction-stimulus-locked LRPs, divided into three subsets as a function of response speed. As suggested by this figure, the onset of the LRP varied as a function of RT, \( F(2,10) = 10.08 \). The mean latencies of the onset of the LRP were 169.0, 251.7, and 306.3 ms for the fast, medium, and slow subsets, respectively. In summary, the present study did have sufficient power to detect an effect on the LRP that is consistent with Gratton’s Rule.

Discussion
Previous work has shown that the height of the stimulus-locked LRP at the mean time of response initiation is approximately constant across levels of RT in uncued, response-time tasks (Gratton et al., 1988). It has also been shown that the height of the response-locked LRP is approximately constant across levels of RT in cued/speeded tasks (Hackley & Miller, 1995). The present

<table>
<thead>
<tr>
<th>Division measure</th>
<th>Best subset</th>
<th>Middle subset</th>
<th>Worst subset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>2.83 ± 0.67 μV</td>
<td>2.86 ± 0.81 μV</td>
<td>2.38 ± 0.45 μV</td>
</tr>
<tr>
<td>Peak force</td>
<td>2.80 ± 0.82 μV</td>
<td>2.34 ± 0.54 μV</td>
<td>2.96 ± 0.60 μV</td>
</tr>
<tr>
<td>Time to peak force</td>
<td>2.37 ± 0.62 μV</td>
<td>3.05 ± 0.65 μV</td>
<td>2.63 ± 0.76 μV</td>
</tr>
<tr>
<td>Force gain rate</td>
<td>2.33 ± 0.80 μV</td>
<td>2.84 ± 0.66 μV</td>
<td>2.91 ± 0.56 μV</td>
</tr>
<tr>
<td>Integrated force to peak</td>
<td>2.57 ± 0.70 μV</td>
<td>2.61 ± 0.70 μV</td>
<td>2.39 ± 0.60 μV</td>
</tr>
</tbody>
</table>

Table 3. Summary of the Response-locked Lateralized Readiness Potentials at the Time of Electromyographic Activity Onset as a Function of Data Subset

Figure 4. Grand-average stimulus-locked midline, centroparietal waveforms for each subset from each of the five analyses. These waveforms represent the mean of the Cz and Pz waveforms. Note the differences in amplitude and timing that begin approximately 200 ms after stimulus onset in the top panel; these are differences in the P300 component as a function of response time. Note also the apparent differences in the negative peaks near the time of stimulus onset in the second, fourth, and bottom panels; these are differences in the CNV as a function of response kinetics.
study extends this pattern to LRPs that have been response-locked to EMG onset in an uncued, response-time task. Thus, the pattern of results that demonstrates what we have labeled “Gratton’s Rule” appears to be quite robust. As stated earlier, this supports the idea that the LRP is an on-line index of response preparation and that the LRP must exceed a fixed threshold for an overt response to be produced.

The present study has also shown that similar rules seem to apply when the data are divided in terms of four different measures of response kinetics, at least when only preresponse LRPs are considered. This new pattern of results is important for two reasons. First, with regard to the indexing function for the LRP, this supports the idea that the LRP is only a measure of the preparation to use a particular hand (or foot) and is not a measure of certain other elements of motor programming, such as the number of force-units to be recruited or the duration of the motor output command (see Ulrich & Wing, 1991; Ulrich, Wing, & Rinkenauer, 1995). Put simply, the LRP in speeded tasks is unaffected by subsequent response kinetics.

Second, with regard to the growing list of cognitive experiments that have employed the LRP to make inferences about the onset and duration of response selection (e.g., De Jong et al., 1990; Gratton et al., 1988; Leuthold et al., 1996; Miller & Ulrich, 1998; Mordkoff et al., 1996; Osman & Moore, 1993; Smid, Lamain, Hogeboom, Mulder, & Mulder, 1991; Ulrich, Rinkenauer, et al., 1998), the present finding that spontaneous variations in response kinetics do not influence the LRP should be seen as very encouraging. In particular, these results would seem to rule out alternative explanations that might try to explain any observed differences in the LRP (across levels of some independent variable) in terms of the subsequent amount of produced force, as opposed to the time that was required to choose the response.

It should be noted, however, that our results do not rule out the possibility that instructed differences in other aspects of the response might influence the LRP. In fact, there is already some evidence that more complex responses (e.g., sequences of finger movements, as opposed to a single flexion by a single digit) are preceded by greater amounts of LRP activity (e.g., Hackley & Miller, 1995). Furthermore, our analyses did not address the possibility that different amounts of EMG activity might be preceded by different amounts of LRP activity, or that different amounts of force might correspond to different amounts of LRP activity that occurs after response initiation. These questions are beyond the scope of this paper (partly because of the problem of reafferent effects on any LRPs measured after response onset), but are important topics for future research.

In contrast to the LRP, the present study did find that the magnitude of the CNV is directly related to some aspects of subsequent response kinetics (in particular: peak force and integrated force to peak). Similar relationships have been observed in a variety of other tasks (see, e.g., Bruni & Vingerhoets, 1980; Slobounov, Ray, & Simon, 1998; Sommer et al., 1994), so this pattern has wide generality. However, the relationship between the CNV and response speed appears to be much more dependent on the specific task used. The present study found no such relationship, whereas others have found that larger CNVs precede faster responses (e.g., Hackley & Miller, 1995; see, also, McCullum, 1988; Rockstroh et al., 1989), as well as effects on response speed of transcranial stimulation (e.g., Hasbroucq et al., 1999). Instead, other mid-line components, such as the P300, seem to provide

### Table 4. Summary of the Peak Contingent Negative Variations Near the Time of Stimulus Onset as a Function of Data Subset

<table>
<thead>
<tr>
<th>Division measure</th>
<th>Best subset</th>
<th>Middle subset</th>
<th>Worst subset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>$-2.99 \pm 0.66 \mu V$</td>
<td>$-3.61 \pm 0.97 \mu V$</td>
<td>$-3.70 \pm 1.21 \mu V$</td>
</tr>
<tr>
<td>Peak force*</td>
<td>$-4.23 \pm 0.81 \mu V$</td>
<td>$-2.95 \pm 0.98 \mu V$</td>
<td>$-2.95 \pm 0.88 \mu V$</td>
</tr>
<tr>
<td>Time to peak force</td>
<td>$-3.28 \pm 0.89 \mu V$</td>
<td>$-3.22 \pm 0.80 \mu V$</td>
<td>$-3.53 \pm 0.80 \mu V$</td>
</tr>
<tr>
<td>Force gain rate</td>
<td>$-3.80 \pm 1.24 \mu V$</td>
<td>$-2.96 \pm 0.69 \mu V$</td>
<td>$-3.02 \pm 0.95 \mu V$</td>
</tr>
<tr>
<td>Integrated force to peak*</td>
<td>$-4.18 \pm 0.80 \mu V$</td>
<td>$-2.93 \pm 0.95 \mu V$</td>
<td>$-2.99 \pm 0.97 \mu V$</td>
</tr>
</tbody>
</table>

Note: * indicates a significant main effect ($p < .05$) of data subset.

### Table 5a. Summary of the Peak Magnitudes of the P300 Component as a Function of Data Subset

<table>
<thead>
<tr>
<th>Division measure</th>
<th>Best subset</th>
<th>Middle subset</th>
<th>Worst subset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time*</td>
<td>$10.45 \pm 2.14 \mu V$</td>
<td>$10.66 \pm 2.55 \mu V$</td>
<td>$8.23 \pm 2.11 \mu V$</td>
</tr>
<tr>
<td>Peak force</td>
<td>$8.74 \pm 2.48 \mu V$</td>
<td>$9.36 \pm 2.53 \mu V$</td>
<td>$8.81 \pm 2.15 \mu V$</td>
</tr>
<tr>
<td>Time to peak force</td>
<td>$9.31 \pm 2.74 \mu V$</td>
<td>$9.10 \pm 2.25 \mu V$</td>
<td>$8.51 \pm 2.06 \mu V$</td>
</tr>
<tr>
<td>Force gain rate</td>
<td>$8.94 \pm 2.82 \mu V$</td>
<td>$9.14 \pm 2.31 \mu V$</td>
<td>$8.60 \pm 2.01 \mu V$</td>
</tr>
<tr>
<td>Integrated force to peak*</td>
<td>$8.90 \pm 2.50 \mu V$</td>
<td>$9.25 \pm 2.44 \mu V$</td>
<td>$8.76 \pm 2.30 \mu V$</td>
</tr>
</tbody>
</table>

Note: * indicates a significant main effect ($p < .05$) of data subset.
more consistent estimates of processing speed that are unaffected by response kinetics (Coles et al., 1985; but, see also, Doucet & Stelmack, 1999).

Finally, when one considers the entire pattern of results across a variety of studies, it becomes clear that certain indexing functions are probably task specific. In other words, the relationship between a physiological measure and a cognitive process might vary across experimental tasks and procedures. For example, the idea that the LRP is a selective measure of the preparation to use a particular hand (regardless of response kinetics) has only been shown to hold true for cued and uncued, speeded tasks (Sommer et al., 1994; the present study). The same idea has actually been ruled out for some uncued, unspeeded tasks (Ray et al., 2000). Therefore, it would seem to be essential that the background work that is conducted or cited as supporting a given indexing function (to be used to make inferences about cognitive processes) be from tasks that are as similar as possible to those that will be used in the critical experiment.

### REFERENCES


Cortico-spinal inhibition reflects time to peak force in divided and focused attention. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 164–182.


Mordkoff, J. T., & Gianaros, P. (2000). Detecting the onset of the lateralized

(Received April 6, 2000; Accepted February 27, 2001)