

# The Temporal Selectivity of Additive Factor Effects on the Reaction Process Revealed in Erp Component Latencies

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## The temporal selectivity of additive factor effects on the reaction process revealed in ERP component latencies

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### Abstract

An experiment was conducted to relate individual components of the event-related brain potential to specific stages of information processing in a two-choice reaction time (RT) task in a group of undergraduate students. Specifically, the latency of the P300 component and the lateralized readiness potential (LRP) were studied as a function of variations in stimulus degradation and response complexity. It was hypothesized that degrading the stimulus would delay the P300 and LRP to the same extent as RT, and that increasing response complexity would affect RT but not P300 latency. The extant literature did not permit any hypothesis regarding the effect of response complexity on LRP latency. The two task variables were found to have additive effects on RT. As predicted, variations in stimulus degradation influenced the latencies of both components, whereas alterations in response complexity had no effect on P300 latency. A significant new finding was that the onset latency of the LRP remained unchanged across levels of response complexity. The overall pattern of results supports the notion of temporal selectivity of stage manipulations that is derived from discrete stage models of human information processing. Furthermore, these results refine the functional interpretation of the LRP by indicating that within the conceptual framework of a stage model the processes this component indexes succeed the start of response choice but precede the start of motor programming.

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### 1. Introduction

In the last decade, there has been a dramatic increase in the combined use of event-related brain potential (ERP) and reaction time (RT) measures to test

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models of information processing. In particular, the lateralized readiness potential (LRP) has been used as a measure of hand-specific response system activation to detect the transmission of partial stimulus-information to the motor system before stimulus analysis has been completed (De Jong et al., 1988; Gratton et al., 1988; Miller and Hackley, 1992; Smid et al., 1987). The experiments addressing this issue were often designed in such a manner that the various features of the stimulus induced a competition between responses with either hand or between giving a response and withholding one. Lateralization of the LRP in the direction of the incorrect response hand or the emergence of an LRP when a response was withheld, as reported in these studies, demonstrated that partial information about the stimulus was transmitted to the response system before stimulus processing had finished. Either finding supported models in which stimulus information is passed on to the response system continuously (Eriksen and Schultz, 1979), or in more than one discrete chunk (Miller, 1982), demonstrating that there are limits to the applicability of more elementary discrete serial stage models of information processing (Sternberg, 1969; Sanders, 1980).

To our knowledge, there have been no attempts to relate the LRP to models in which information processing is typically characterized as a series of discrete stages. This is surprising, particularly in view of the fact that another frequently studied ERP component, the P300, has derived much of its functional interpretation from its sensitivity to some stage manipulations and its relative insensitivity to others (McCarthy and Donchin, 1981, 1983; Magliero et al., 1984). For example, in testing the hypothesis that P300 latency is sensitive to variations in stimulus, but not response, processing demands, McCarthy and Donchin (1981) selected two variables that were known to have additive effects on RT, stimulus discriminability and stimulus-response (S-R) compatibility. Recall that according to the reasoning of the additive factors method (AFM, Sternberg, 1969) this additivity suggests that these two factors influence different stages of processing. The results indicated that both factors influenced RT, but that only one factor, stimulus discriminability, affected P300 latency. This experimental dissociation of factor effects (on RT and P300 latency), interpreted in the context of the AFM, provided support for the hypothesis under examination by McCarthy and Donchin.

Thus, the use of the AFM may strengthen interpretations about the functional significance of ERP components. However, relating the latencies of individual components of the ERP to specific stages of processing may also bring information on some of the assumptions on which stage models are built. Specifically, discrete serial stage models predict that factor effects are temporally selective; that is, a factor should have its effect only during a certain time interval that is smaller than RT. It is quite difficult to isolate a part of the total reaction process using RT measures alone. The potential of ERP latencies is that they may index the duration of subsets of processes that make up total RT, with factor effects on component latencies providing direct tests of temporal selectivity. A strong case for temporal selectivity of effects could be made if the effect size of manipulations on an ERP component would equal the effect size on RT, while the absolute latency of the component well preceded the response. This indicates that on a given

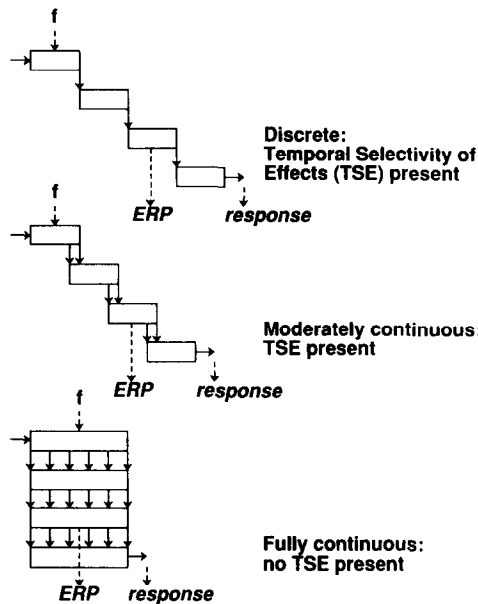


Fig. 1. The temporal selectivity of the effect of a task factor  $f$  for discrete, moderately continuous, and fully continuous types of models. Temporal selectivity of factor effects is derived from the comparison of effect sizes of  $f$  on the latencies of an ERP component and the response.

moment in time, well before the response, at least something is delayed to an equal extent as RT, and it would suggest that the total effect of an experimental manipulation has elapsed long before a response is given.

Strictly, the prediction of temporal selectivity of factor effects is not unique to discrete stage models. It is imaginable that information is being passed on from one stage to the next in a continuous manner, but that this flow lasts only a short time in comparison to the stage duration. Such a model could be labeled moderately continuous, as opposed to a fully continuous model, in which every stage would be smeared out from the moment of stimulus presentation until the response. It can be seen in Fig. 1 that temporal selectivity is obtained in a serial discrete stage model, but not in fully continuous models. However, temporal selectivity of effects will also be obtained in the moderately continuous model, as long as there is no temporal overlap between the affected stage and the stage that generates the ERP component. This would imply that one cannot discriminate between discrete and moderately continuous models by studying factors effects on ERP component latencies. On the other hand, it is known from previous LRP studies that partial information from a stimulus may extend its effects throughout the information processing system to even the motor stages, where it can differentially activate responses (De Jong et al., 1988; Gratton et al., 1988; Miller and Hackley, 1992; Smid et al., 1987). Therefore, it may be argued that ERP measures are sensitive enough to detect realistic degrees of partial information being transmitted.

In the present experiment the effects of variations in stimulus quality and response complexity on the latencies of P300 and LRP were studied. These factors were expected to have additive effects on RT. Following the hypothesis that P300 latency specifically indexes the duration of stimulus evaluation processes, variations in stimulus quality, but not in response complexity, were expected to affect P300 latency.

There is both ERP and neurophysiological evidence that the LRP indexes hand-specific response system activation (for reviews see Coles, 1989; Miller and Hackley, 1992). Consequently, in a stage model the LRP would be assumed to be elicited by the onset of the response selection stage or some later stage. This assumption generates the prediction that the effects of all variables affecting earlier stages of processing will be equal in magnitude for LRP latency and RT. For instance, the effects of stimulus degradation would be equally large on LRP and RT. In a continuous-flow model, it is expected that partial evidence about the identity of the stimulus is transmitted to its associated response channel, thereby priming that response to some below-threshold level. Under these circumstances, information about the stimulus would still be accumulating as the response system is being activated and, as a result, stimulus degradation would not be expected to have its full effect at the onset of the LRP. Consequently, the effects of degradation on the onset latency of LRP would be smaller than on RT. Predictions regarding the effect of variations in response complexity on the onset latency of the LRP are less obvious because the precise stage of motor preparation or execution that is indexed by LRP is unknown. Thus, the stage associated with the programming of more complex responses may precede or follow the moment LRP-onset latency is determined. Therefore, establishing the effect of response complexity on LRP-onset latency will contribute to refining the functional interpretation of LRP.

## **2. Method**

### *2.1. Subjects*

18 undergraduate students at the University of Amsterdam received course credits for their participation. Each subject took part in either two morning or two afternoon sessions. The data of one subject were lost due to technical failure, three others were omitted from the data set because there was no consistent lateralization in the LRP in one or more experimental conditions.

### *2.2. Procedure*

Subjects were required to make a left- or right-hand response upon presentation of the digit '2' or '5'. A digit consisted of a dot pattern that was surrounded by a frame also consisting of dots. Each dot comprised six by six pixels on the screen. Digits were degraded by placing 12 dots from the frame at random positions in the

field within the frame on positions not occupied by the 14 to 17 dots of the digit. There were seven degraded versions of each digit. The size of the frame was 23 mm horizontally and 29 mm vertically on a monitor located 80 cm from the subject. Presentation time was 200 ms and the interval between the offset of a stimulus and the onset of the next varied randomly between 1500 and 2200 ms. During this interval a central fixation cross was presented. Each experimental session consisted of four blocks of 112 trials, corresponding to two factors (stimulus degradation, response complexity) with two levels. In the simple-response conditions, subjects gave a single keystroke with the index finger. In the complex-response conditions, subjects were required to press a sequence of three keys, using the index, ring, and then middle fingers (i.e. the 2nd, 4th and 3rd digits, Hackley and Miller, 1989; Miller and Hackley, 1992). The latency of the first keystroke in this sequence provided the RT. The order of blocks was counterbalanced across sessions and subjects. In the second session the mapping of stimuli to responses was switched. Training occurred just before each experimental session, repeating trial blocks for each condition until the error percentage was below 10%. Subjects were instructed to respond as rapidly as possible while keeping their error rate low. After each block, the subject received feedback on the mean and variability of RT, and the number of errors.

### 2.3. Recordings

The electroencephalogram (EEG) was recorded from a bipolar derivation between  $C_3$  and  $C_4$  and from Pz (Jasper, 1958) by means of tin electrodes attached to an electro-cap. The vertical (above and below the pupil of the right eye) and horizontal (at the outer canthus of each eye) electro-oculogram (EOG) were recorded. A ground electrode was placed on the forehead. Electrode impedance was kept below 8 kOhm. Amplifiers were set to a time constant of 5 s and 35Hz low-pass filtering. 200-Hz sampling started at 150 ms before stimulus onset and lasted for 1600 ms.

### 2.4. Data analysis

Trials with an incorrect response, trials with an RT deviating more than 2.5 standard deviations from the mean and trials with artifacts (saturation of the AD-converter or an EEG-amplitude greater than 150  $\mu$ V) were excluded. Ocular artifact was controlled according to Woestenburg et al. (1983). Pre-stimulus samples served as baseline. LRPs were computed for each condition by subtracting, point-by-point, the  $C_3 - C_4$  ERPs for right-hand trials from those for left-hand trials. Signal analyses were done on stimulus (S)-locked signals and on response (R)-locked signals. S-locked means that each point in the average ERP is based on points from single trials that follow the stimulus by the same amount of time. R-locked means that each point in the average ERP is based on points from single trials that precede the response by the same amount of time. It was expected that effects on the duration of the stimulus-to-ERP component interval affect the

S-locked ERP and effects on the duration of the ERP-to-response interval affect the R-locked ERP. For instance, variations in stimulus quality were expected to affect the latency of S-locked but not R-locked P300 and LRP, and variations in response complexity were expected to affect R-locked, but not S-locked P300 latency (cf. Osman and Moore, 1993). For each subject and experimental condition the waveforms from Pz were filtered low-pass ( $-3\text{dB}$  at  $3.6\text{Hz}$ ).<sup>1</sup> P300 latency was taken as the latency of the largest maximum in a window extending from 250 to 600 ms for S-locked waveforms and from 175 before to 175 ms after the response for R-locked waveforms. The onset of LRP was determined in a manner similar to Osman et al. (1992).<sup>2</sup> It was taken as the first point in time at which the LRP waveform consistently exceeded a criterion of 2.5 times the standard deviation of a noise distribution. The variance of the noise distribution was estimated by averaging the variances (in voltage over time) of the four wave forms during the first 200 ms following stimulus onset. To be considered consistently above criterion, the onset and voltage during each of the next two 50 ms windows had to exceed the criterion. A specific criterion was calculated for each subject, and was applied to both S-locked and R-locked LRPs in each of the four experimental conditions.

### 3. Results

Table 1 shows the effect of stimulus degradation and response complexity on mean RT and S-locked and R-locked ERP latencies, with associated percentages of errors between parentheses. Reported  $F$ -values were significant at a 5% level, with associated  $df$  of (1,13), unless stated otherwise. As is apparent in Table 1, RT was increased by both stimulus degradation and response complexity ( $F = 112.8$  and  $F = 14.6$ , respectively). These factors did not interact ( $F = 0.16$ ). The proportions of errors were small and increased only by stimulus degradation ( $F = 8.2$ ; all other  $F$ s  $< 1$ ).

Fig. 2 shows the effects of stimulus degradation and response complexity on grand average waveforms at Pz. It can be seen that stimulus degradation delayed the S-locked P300, but not the R-locked P300. Response-complexity had the opposite effect: it delayed the R-locked P300, but not the S-locked P300. These visual observations were confirmed by analyses of the P300 latency data. The interval between stimulus onset and the P300, indexed by the latency of the S-locked P300, was increased by stimulus degradation, but not by response complexity ( $F = 129.0$ , and  $F = 4.0$ , respectively). These factors did not interact ( $F = 2.6$ ). The interval between the P300 and the response, indexed by the latency of the

<sup>1</sup> For one subject a 6.9 Hz filter was used, because stronger low-pass filtering turned P300 and a later component into one unimodal component.

<sup>2</sup> This method was preferred over one that defines the attainment of a certain proportion of the maximum amplitude of LRP as its onset (Smulders et al., in press), because we expected that the maximum amplitude of the LRP would be systematically affected by the response complexity factor (Hackley and Miller, 1995).

Table 1

The effects of stimulus degradation and response complexity on mean reaction time and latencies of the stimulus-locked and the response-locked P300 and LRP. Note that for the response-locked ERPs, latencies are given with respect to the moment of response: negative values indicate that the ERP precedes the response. These values are in ms. The percentage of errors is given between parentheses

	Intact	Degraded	Difference
RT			
Simple	385 (3.1)	421 (4.5)	36 (1.4)
Complex	411 (3.7)	445 (5.0)	34 (1.3)
Difference	26 (0.6)	24 (0.5)	-2 (-0.1)
S-locked P300			
Simple	390	427	37
Complex	384	414	30
Difference	-6	-13	-7
R-locked P300			
Simple	14	11	-3
Complex	-11	-16	-5
Difference	-25	-27	-2
S-locked LRP			
Simple	241	266	25
Complex	240	276	36
Difference	-1	10	11
R-locked LRP			
Simple	-133	-132	1
Complex	-156	-153	3
Difference	-23	-21	2

R-locked P300, was increased by response complexity, but not by stimulus degradation ( $F = 19.5$  and  $F = 2.7$ , respectively). Again, these two factors did not interact ( $F = 0.22$ ).

Fig. 3 shows the effects of stimulus degradation and response complexity on the LRP. It can be seen that stimulus degradation delayed the onset of the S-locked LRP, but not the R-locked LRP. Response-complexity had the opposite effect: it delayed the onset of the R-locked LRP, but not the S-locked LRP. These observations were confirmed by analyses on the LRP onset latency data. The interval between stimulus onset and the onset of the LRP, indexed by the latency of the S-locked LRP, was increased by stimulus degradation, but not by response complexity ( $F = 13.3$  and  $F = 0.25$ , respectively). These factors did not interact ( $F = 0.37$ ). The interval between the LRP onset and the response, indexed by the latency of the R-locked LRP, was increased by response complexity, but not by stimulus degradation ( $F = 17.9$  and  $F = 0.11$ , respectively). Again, these factors did not interact ( $F = 0.14$ ).

#### 4. Discussion

The purpose of the present experiment was to relate individual ERP components to specific stages of processing defined by the logic of the AFM. This had



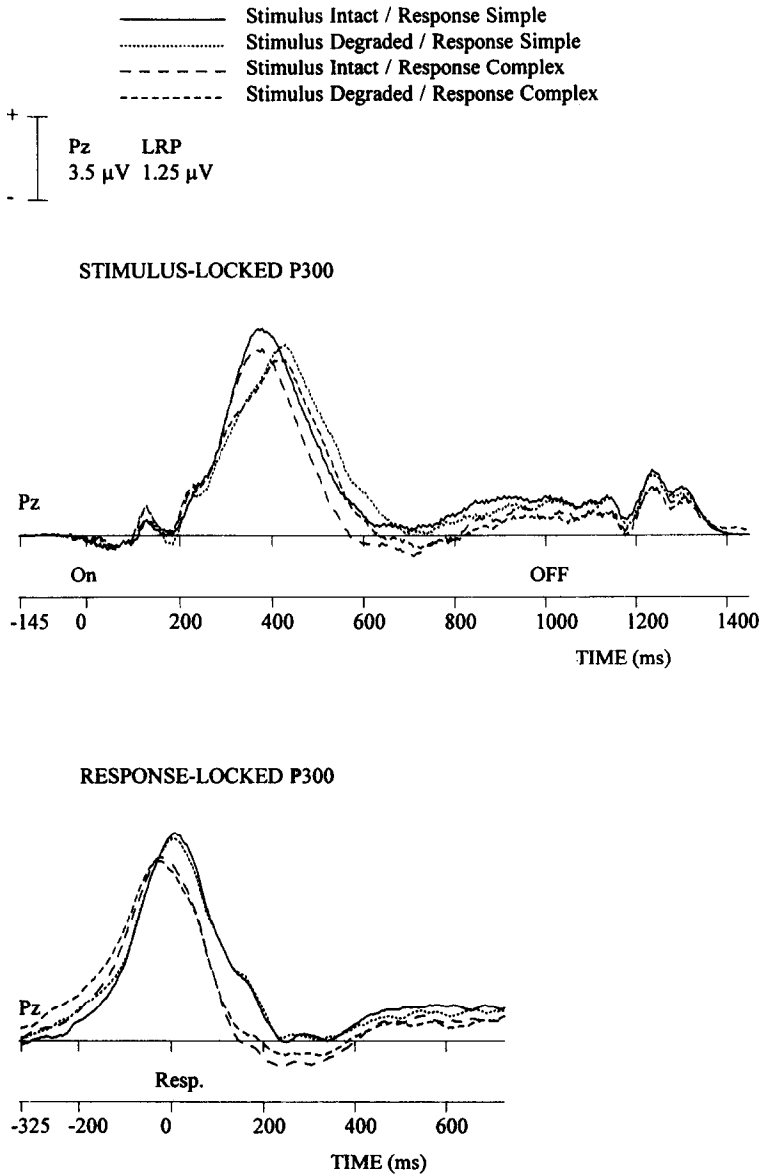


Fig. 2. The effects of stimulus degradation and response complexity on stimulus-locked and response-locked ERPs at Pz.

been done in previous research for one component, the P300, but not for another one, the LRP. The results of this experiment make at least three contributions to the literature. First, they demonstrate that factor effects on ERP component latencies can be used to determine if the additivity of factor effects on RT is

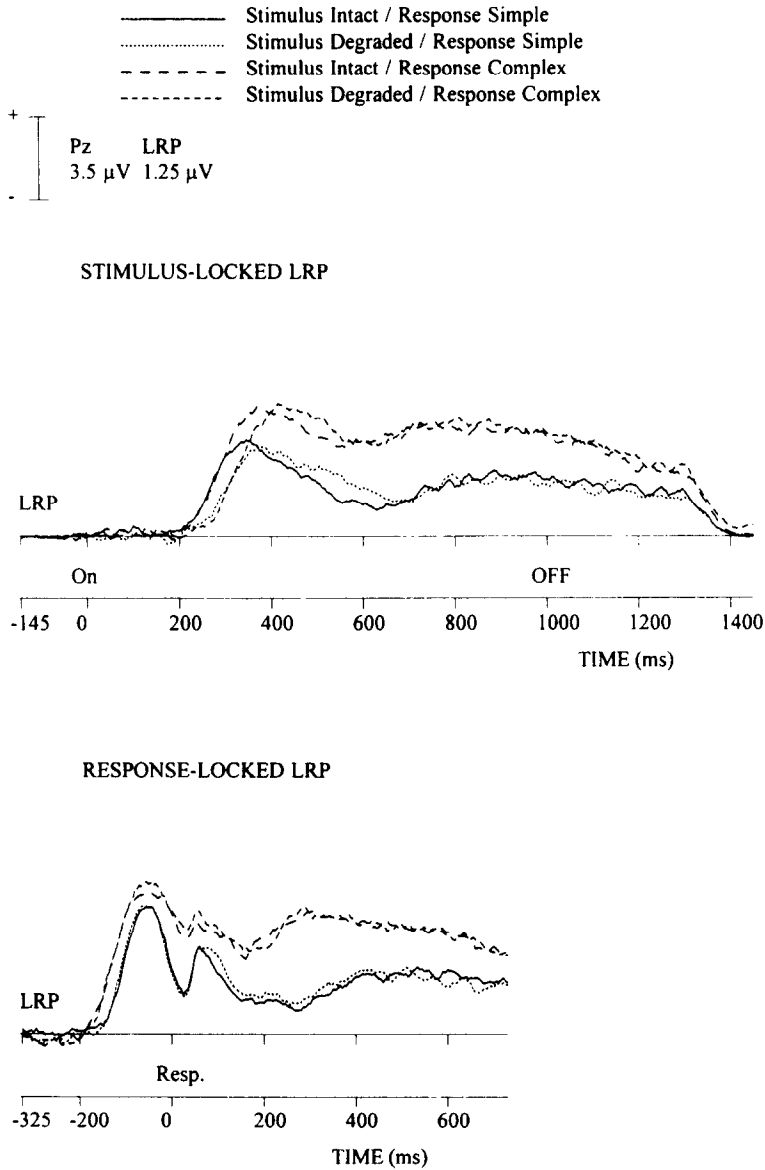


Fig. 3. The effects of stimulus degradation and response complexity on stimulus-locked and response-locked LRPs.

indeed a manifestation of selective influences on different portions of the S-R interval. Second, the results support the conventional view that P300 latency is sensitive of the duration of stimulus evaluation processes, whereas it is independent of the duration response-related processes. Third, they help refine our understanding of the functional significance of the LRP.

The results of this experiment show that variations in stimulus degradation and response complexity have additive effects on RT. According to the logic of the AFM, this result is congruent with a two-stage model in which each of these factors exclusively affects a stage. However, this analysis does not specify if the effects of stimulus degradation and response complexity were limited to a particular portion of the total reaction process, nor does it specify the order of the two inferred stages. Further evidence of stage independence of stages would be obtained if it could be shown that the delays on RT produced by the two manipulations occurred in non-overlapping time segments. At the very least, this result would rule out fully continuous models because they would predict that delays on RT would be distributed across virtually the entire stimulus-response interval. Also, it would argue against other models that assume that partial information is used to activate a response while stimulus encoding is going on.

The ERP results revealed a clear dissociation between the effects of stimulus degradation and response complexity on the intervals indexed by the S-locked and the R-locked ERP components. Stimulus degradation delayed the interval between onset of the stimulus and the occurrence of P300 and LRP, but not the interval between these components and the overt response. Response complexity had exactly the opposite effect: it delayed only the interval between the ERP components and the response. Clearly, this result is consistent with a stage order in which the stage affected by stimulus degradation precedes the stage affected by response complexity.

As argued earlier, the best evidence for temporal selectivity of effects would consist of two elements. First, the effects of stage manipulations should be of equal magnitude for ERP latency and RT. Second, the ERP component should well precede the response. The results in Table 1 show that the first condition was met for the effects of variations in stimulus quality on the latencies of the P300 and LRP. An apparently slight deviation from this pattern occurred for simple responses: the effect of degradation on the S-locked LRP appears to be smaller than on RT. This effect had no statistical significance, however, and was not corroborated by a complementary effect of degradation on the R-locked LRP. The second condition was met only by the LRP. Both the S-locked P300 latency and the R-locked P300 latency occurred very close in time to the overt response. Indeed, in the simple response conditions the peak of P300 occurred even after the response (cf. Table 1).<sup>3</sup> In contrast to the P300, the LRP onset occurred well before the execution of the overt response. These results for the LRP support the notion of temporal selectivity of degradation effects on RT, as predicted by discrete stage models. It could be argued that the LRP is so tightly connected to the moment of the overt response, that it will never be dissociated from it. If this is the case, it

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<sup>3</sup> It cannot be ruled out that the latency of the P300 is relatively long only because the moment of its peak was used as a parameter instead of its onset. It is possible that earlier portions of this component are affected by factor effects in much the same way as the peak is. However, using another parameter than the peak is very unusual, since it greatly increases the risk that overlapping other components bias the parameter. For a discussion of this issue, see Meyer et al. (1988).

would not be surprising that degradation does not affect the LRP-to-RT interval. However, De Jong et al. (1990) have demonstrated that intended responses can be stopped after LRP onset, thereby dissociating LRP and the response. Moreover, the criticism is refuted by the present results showing large effects of response complexity on the LRP-to-RT interval. In functional terms, the results suggest that stimulus degradation has no delaying effects anymore during the period of time that responses are programmed.

The results of this experiment also have implications for the functional interpretation of the LRP. From the notion that the LRP represents hand-specific response system activation, it follows that the LRP is likely to be generated somewhere after the beginning of the response choice stage. Our findings suggest that programming more complex responses has no effect on the onset latency of LRP. It follows that the LRP may now be more precisely located to a point in time after the start of response choice, but preceding motor programming. The factor associated with the response choice stage, S-R compatibility (Sanders, 1980), has been shown to be additive with response complexity (Inhoff et al., 1984). According to the AFM, this suggests that response choice and motor programming are two separate processing stages. Consequently, there is still some room left for the exact functional interpretation of the LRP: It might reflect processes still within the functional stage of response choice, or in any putative stage in between response choice and motor programming.

Hackley and Miller (1995) have shown that if a precue specifies the response hand, and a second stimulus signals whether a response should be executed or withheld, the LRP is larger during the preparatory interval for a complex than for a simple response. Complementing this result, Fig. 3 reveals that when the imperative stimulus specifies the response hand, as it did in our experiment, there is no such amplitude difference until a point in time well after the onset of the LRP. This is consistent with the notion that the response hand is selected before the additional response parameters involved in making a complex movement are specified.

In summary, in the present experiment stimulus degradation had its effects only between the onset of the stimulus and the occurrence of P300 and LRP, and response complexity delayed only the interval between these ERP components and the response. These results support the notion of temporal selectivity of factor effects that is predicted by discrete processing models, thereby increasing the confidence in the postulation of multiple processing stages on the basis of the additivity of factor effects. At the same time, the results extend the utility of LRP in studies of mental chronometry by relating experimental factor effects on its latency to those on RT. More research is needed to further specify the functional significance of LRP, increasing its utility in mental chronometry.

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