

Stimulus–Response Compatibility and Automatic Response Activation: Evidence From Psychophysiological Studies

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Effects of dimensional overlap between stimuli and responses on partial response activation were investigated within a priming paradigm with the help of event-related potentials. The likely position of a target stimulus (requiring a left or a right reaction) was indicated by an arrow precue. To test whether automatic response activation processes are triggered by the cue, the lateralized readiness potential was computed. It was found that responses congruent to the direction of the cue were activated about 200 ms after cue onset. This early process was unaffected by specific cue–response contingencies and was completely missing when a nonspatial (color) cue was used. A second response activation phase was observed, which was partially controlled by specific response instructions and subjective expectancies. It is concluded that when stimuli and responses overlap with respect to spatial attributes, automatic response activation processes are triggered, which may later be replaced by the activation of an expected response.

It is a well-known fact that the performance of participants in an experimental task is influenced by the way that stimuli and responses are paired with each other. For example, it is easier to respond to a red visual stimulus by pressing a red response key and to a green visual stimulus by pressing a green response key than it is to react to a red stimulus with a green key and to a green stimulus with a red key. When verbal responses to visually presented letters are required, participants have more difficulty in pairing the letter with the name of a digit or with the name of another letter than with its own name. Generally, responding to a stimulus is easier when the stimulus and the response connected to it share one or more properties.

The fact that the performance of participants is influenced by the similarity of stimulus and response properties is usually referred to as stimulus–response (S-R) compatibility (cf. Fitts & Deininger, 1954; Fitts & Seeger, 1953). S-R compatibility effects can be observed when stimuli and responses are similar with respect to a specific dimension, like being colored or being distributed in space. These shared attributes can either be relevant for response selection or not. In the first case, these attributes are systematically related to the required responses in a task. For example, task performance has been found to be better when horizontally aligned stimuli are mapped to response keys

located directly below than when these stimuli are randomly assigned to specific response keys (Morris & Grant, 1955; see also Duncan, 1978). In the second case, stimulus and response sets also share certain attributes, but these are unrelated to the required responses. In an experiment by Wallace (1971), a left-hand response was required to squares and a right-hand response was required to circles that were presented randomly on the left or the right side. Although spatial location was irrelevant for response selection, reaction time (RT) was faster when a stimulus appeared on the side corresponding to the required response (see also Simon, 1967, 1969; Simon, Craft, & Webster, 1973; Simon & Rudell, 1967; Simon & Small, 1969).

The aforementioned experiments have demonstrated that performance is better when a stimulus and the response connected to it share one or more attributes on a (relevant or irrelevant) dimension than in a situation where they differ with respect to these attributes. The aim of this article is to study the mechanisms responsible for this effect with the aid of electrophysiological measurements.

Stimulus–Response Compatibility: The Dimensional Overlap Model

The idea that S-R compatibility is a rather broad phenomenon has been explicitly developed by Kornblum, Hasbroucq, and Osman (1990). These authors have formulated a general model of S-R compatibility that serves both to classify different types of compatibility tasks and to provide a general account of the mechanisms responsible for compatibility effects to occur in different experimental situations. According to Kornblum et al., in order for S-R compatibility effects to occur, it is necessary that a stimulus set and a response set share specific properties or, in other words, that an S-R ensemble is characterized by dimensional overlap. The overlapping dimensions may or may not

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be relevant for response selection. When there is dimensional overlap on a relevant dimension, two processes are triggered by the presentation of a stimulus. On the one hand, a response is activated that shares an attribute with the stimulus. This response activation process is presumed to be elicited automatically. Adopting a proposal by Kahneman and Treisman (1984), Kornblum et al. (1990, pp. 261–262) distinguished between strongly and partially automatic processes. Whereas the former process is completely independent of attention, the latter may be attenuated or facilitated by attention, although it will not be fully suppressed. If response activation was strongly automatic, this process would be independent of the response relevance of an eliciting stimulus attribute. If it was only partially automatic, responses would be less strongly activated when the eliciting attribute was irrelevant (Kornblum et al., 1990, pp. 262–263).

In the case of a congruent S-R pairing, the automatically activated response is the response paired to the stimulus by the instructions. When the S-R pairing is incongruent, the activated response differs from the response that was assigned to the stimulus by instruction. In the course of the second process triggered by the stimulus, the correct response is determined. The duration of this response identification process is dependent on the specific S-R assignments given by the experimental instructions. In the case of congruent S-R pairings, the response identification process may proceed relatively fast by applying a simple identity rule, whereas for incongruent pairings, the time-consuming application of a more complicated rule or search will be necessary. According to the model proposed by Kornblum et al. (1990), the benefits obtained with congruent S-R pairings and the costs observed with incongruent pairings result from the interaction of these two processes. When a stimulus shares an attribute with its assigned response, the response identification process will be fast. Moreover, the selected response is identical to the response that has already been activated automatically so that it can be elicited immediately. In the case of an incongruent pairing, response identification will be slowed, and the selected response differs from the response that was automatically activated by the stimulus. In this case, the activated response must be aborted, and the correct response must be initiated, which will cause an additional delay.

The dimensional overlap model of Kornblum et al. (1990) has been proposed as a general account of the processes responsible for the performance benefits and costs obtained in experiments on S-R compatibility. However, it contains a number of hypotheses that may be put to empirical test. As its core assumption, the model predicts that whenever there is dimensional overlap between stimulus and response sets, an automatic response activation process will be elicited after the presentation of a stimulus. Following this initial activation, the correct response will be prepared, which may or may not be identical to the automatically activated response. However, the existence of an automatic activation of a congruent response that is followed by a controlled response initiation process governed by specific response instructions has not yet been empirically verified. Indirect

empirical evidence in favor of these assumptions comes from a study by Georgopoulos, Lurito, Petrides, Schwartz, and Massey (1989; see also Lurito, Georgakopoulos, & Georgopoulos, 1991). In this study, a rhesus monkey was trained to move a handle either directly toward or in a direction perpendicular to a target light whose position changed from trial to trial. During the performance of this task, the activity of directionally tuned cells in the motor cortex was recorded. From these recordings, the neuronal population vector was computed, which is the weighted vector sum of the activities of these neurons, with each neuron signaling its own preferred direction. According to Georgopoulos et al., the neuronal population vector represents the direction of an upcoming movement in space. When the required response was directed toward the target light, the neuronal population vector pointed to the direction of the movement. When the monkey had to move the handle in a direction perpendicular to the target, the vector pointed to the direction of the light at the beginning of each trial and then rotated counterclockwise in time from the direction of the stimulus to the direction of the movement. Georgopoulos et al. regarded these results as evidence that a directional transformation was required in the latter situation, which was achieved by the mental rotation of an imagined movement vector. However, these data can also be interpreted in accordance with the model proposed by Kornblum et al. (1990) as an example for an early automatic activation of a response that is spatially congruent to a stimulus, which is then replaced by a preparation of the correct response.

The response activation processes postulated by the dimensional overlap model are considered to be based on priming mechanisms similar to those elicited in standard priming paradigms (cf. Kornblum et al., 1990, p. 259). Therefore, they may be studied in a priming situation in which the imperative stimulus is preceded by a temporally and physically distinct precue. If the precue and the response are similar with regard to their spatial properties, specific responses are expected to be automatically activated by the precue. After presentation of the target stimulus, the response identification process is initiated to determine the correct response. If this response is identical to the response already activated by the cue, the cue–response pairing may be regarded as congruent. When the primed and the correct response differ, the relationship between cue and response is incongruent. In standard S-R compatibility experiments, both automatic response activation and response identification processes start at the same time and run in parallel, whereas in priming experiments, response activation processes triggered by the cue are temporally separated from response identification processes elicited by the target.¹ A priming paradigm may therefore be a suitable tool to

¹ It should be noted, however, that in the case of priming (S_1 – S_2) paradigms, automatic response activation processes may be triggered by both the cue and the subsequent target stimulus. It is useful to distinguish between cue–response and target–response compatibility, because these may differ within a single trial. In an experiment in which a peripherally presented precue is followed by a peripheral target stimulus, a compatible cue–response map-

study the response activation processes postulated by Kornblum et al. independently from concurrently active response identification processes. In the experiments reported here, a priming paradigm was used and selective response activation processes were monitored with the help of electrophysiological measurements.

Measuring Partial Response Activation: The Lateralized Readiness Potential

To test whether congruent responses are automatically activated when stimuli and responses share certain attributes, it is useful to monitor response preparation processes in a continuous fashion. In the experiments reported here, a measure of partial response activation was derived from the recording of lateralized event-related brain potentials preceding overt responses. When participants are preparing for a response with a particular hand, an increase in negativity can be recorded over those areas of the brain that are supposed to control hand movements (Kutas & Donchin, 1974). Because these negativities are larger at scalp sites contralateral to the prepared hand, this movement-preceding negativity has been termed *lateralized readiness potential* (LRP). The LRP is assumed to reflect the degree to which a left or a right response is activated and is computed on the basis of the electroencephalogram (EEG) potentials recorded above those areas of the motor cortex (C3' and C4') that are supposed to control right-hand and left-hand movements. It is obtained by subtracting the C3'–C4' difference potential obtained prior to a right-hand reaction from the C3'–C4' difference potential recorded prior to a left-hand reaction (for details, see Coles, 1989; Coles, Gratton, & Donchin, 1988; De Jong, Wierda, Mulder, & Mulder, 1988).

If the LRP is to be used to measure partial response activation, it should be directly related to response-related activation processes in the motor cortex. Evidence in favor of this assumption comes from neurophysiological studies showing that the LRP originates, at least partially, from motor regions of the cortex (Arezzo & Vaughan, 1975; Okada, Williamson, & Kaufman, 1982). Gamba and Sasaki (1990) recorded surface-negative, depth-positive potentials in the monkey motor cortex prior to the onset of hand movements, indicating that the generator process is located in the motor cortex. In addition, it has been shown that the activity of cells in the motor cortex closely parallels the onset and the time course of the LRP (Requin, 1985). The existence of a fixed relationship between the LRP and the onset of a peripheral motor response has been demonstrated by Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988).

ping may be accompanied by an incompatible target–response mapping and vice versa. As an example of the first instance, consider the case in which a precue located on the right side (presumably activating a right-hand response) is followed by a left-side target (eliciting a left-hand response activation) that is mapped by instruction to a right-hand response. In contrast, the right-side cue may be followed by a left-side target requiring a left-hand reaction.

In their study, electromyographic activity was found to begin when the LRP reached a fixed threshold value, regardless of the actual response latency or accuracy. Taken together, these findings suggest that the LRP is indeed closely related to the preparation and the execution of motor responses.

The LRP has already been used to demonstrate the existence of automatic response activation processes in a noise-compatibility paradigm (cf. Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton et al., 1988; see also Coles, Gehring, Gratton, & Donchin, 1992, for an overview). In this task, the imperative stimulus was flanked by irrelevant distractor stimuli that were paired by instruction with either the same or a different response as the target. Under these conditions, responses to stimuli flanked by conflicting distractors were delayed as compared to stimuli with congruent distractors (cf. B. A. Eriksen & C. W. Eriksen, 1974; C. W. Eriksen & Schultz, 1979). In the case of congruent distractor elements, the LRP revealed that only the correct response was activated. In the case of conflicting flanker elements, however, the incorrect response was initially activated, followed by the delayed activation of the correct response. Additional evidence for the existence of automatic response activation processes was found in an experiment by Osman, Bashore, Coles, Donchin, and Meyer (1992), in which visual stimuli were presented to the left or the right of fixation, and left-hand or right-hand responses were required to a subset of these stimuli. The LRP revealed an automatic activation of the incorrect response in the condition in which the required response was contralateral to the position of the stimulus.

The LRP has also been used to measure partial response activation in priming experiments (Gehring, Gratton, Coles, & Donchin, 1992; Gratton et al., 1990). In the study by Gehring et al., an imperative stimulus was preceded by a precue that was either uninformative with regard to the identity of the target stimulus or identical to the target in 80% of the trials. The LRP was measured to test whether participants selectively prepared a specific response in the cue–target interval. Although there was no indication of partial response activation when the cue was uninformative, participants were found to prepare the response indicated by the cue when it was highly predictive of the identity of the target.

In a recent study by De Jong, Liang, and Lauber (1994, Experiment 4), effects of spatial correspondences between stimuli and responses on early response activation processes were investigated with the help of the LRP. In accordance with the model of Kornblum et al. (1990), an initial activation of the response side corresponding to the position of the stimulus was found that was independent of specific response instructions. De Jong et al. interpreted this result as evidence for an unconditional process that primes spatially corresponding responses.

In the present experiments, a precuing paradigm was used to test the effects of dimensional overlap between cues and responses on partial response activation processes. A centrally presented precue was followed by an imperative stimulus on the left or the right side, to which participants had

to make a right-hand or a left-hand response. In the majority of the experiments reported below, the precue was an arrow that pointed to either the left or the right side. Because the arrow's direction can be regarded as a spatial attribute and because the responses to the imperative stimulus are also spatially localized, the model of Kornblum et al. (1990) would predict that a congruent response (i.e., a response to the side indicated by the arrow) should be automatically activated by the precue. An arrow pointing to the left side should lead to a partial activation of the left-hand response, whereas a right-pointing arrow should trigger the activation of a right-hand response. If this hypothesis is correct, these processes should be mirrored in corresponding modulations of the LRP waveforms recorded in the cue–target interval.

These assumptions were first tested within a larger study whose primary aim was to investigate the effects of spatial orienting on visual-evoked potentials (Eimer, 1993). At the beginning of each trial, an arrow that pointed to either the left or the right side was presented centrally for 200 ms. On 75% of the trials, one of two imperative letter stimuli (either *M* or *W*) appeared with equal probability on the side indicated by the arrow and on the remaining 25% in the opposite visual hemifield. The cue–target stimulus onset asynchrony (SOA) was 900 ms. In one experimental condition (Eimer, 1993, Experiment 1b), participants were instructed to make a left-hand response when the imperative stimulus

appeared on the left side and a right-hand response when it was presented on the right side. In this condition, the arrow was informative with respect to the response required by the imperative stimulus because this response was correctly indicated by the arrow on 75% of the trials. Participants may thus use this probabilistic information to prepare the indicated response in the interval between cue and target. An analysis of the LRP waveforms recorded in the interval between cue onset and target offset (see Figure 1a) revealed that this was indeed the case. A downward-directed deflection indicates partial activation of the correct response, that is, the response at the side of the upcoming target stimulus. An upward-directed deflection indicates preparation of the wrong response, that is, the response at the side contralateral to the target position. As can be seen from Figure 1a, the correct response was activated on trials in which the target position was correctly indicated by the precue, and the incorrect response was prepared in trials in which the arrow pointed in the wrong direction. In both cases, the LRP waveforms revealed a tendency to activate the response congruent to the arrow's direction. Furthermore, the waveforms showed a bimodal activation pattern, with a first phase starting about 250 ms after cue onset, which then returned back to baseline, and a second phase with an onset of about 300 ms prior to the presentation of the target.

The results of this experiment confirm the finding of

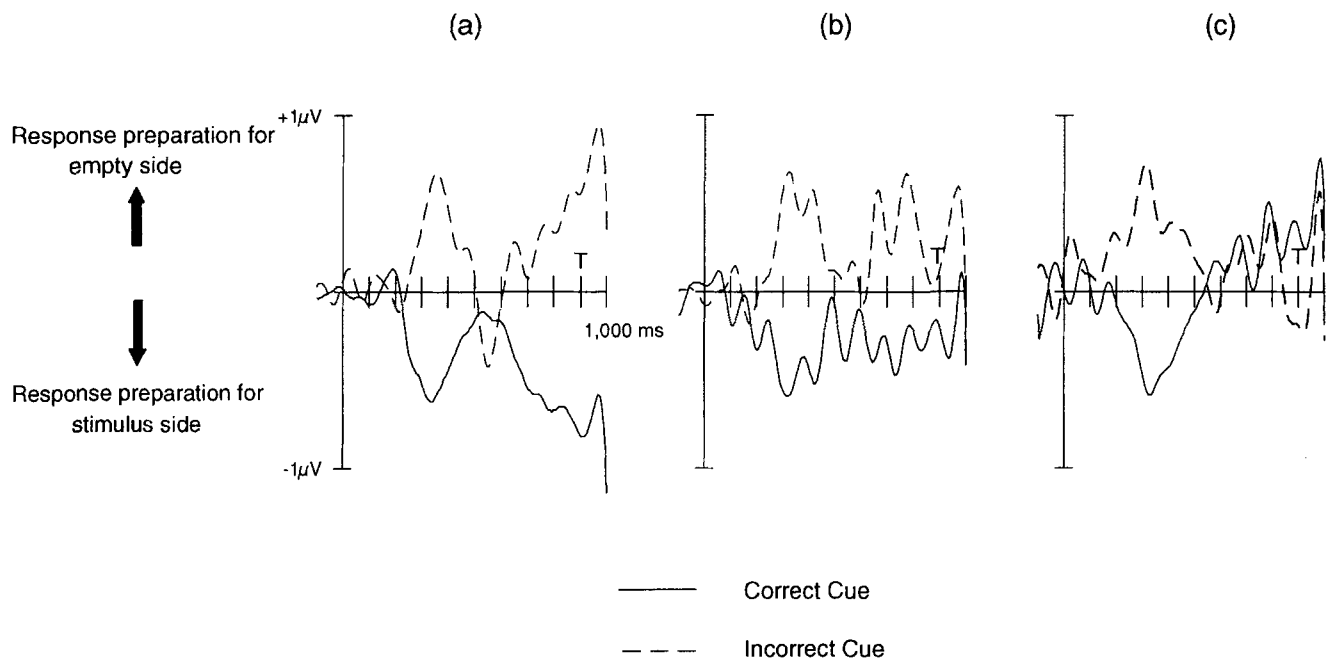


Figure 1. Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for correct and incorrect cues (data from Eimer, 1993). Panel a shows response cue–letter position (Eimer, 1993, Experiment 1b). Panel b shows response cue–letter identity (Eimer, 1993, Experiment 2a). Panel c shows response cue–letter position, with responses always incompatible to the position of the target (Eimer, 1993, Experiment 2b). Downward-directed deflections reflect a negative lateralization measured over motor areas contralateral to the visual field of the imperative stimulus, indicating a tendency to prepare a response at the stimulus's side. Upward-directed deflections indicate response preparation for the empty side. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.) From "Spatial Cueing, Sensory Gating, and Selective Response Preparation: An ERP Study on Visual-Spatial Orienting," by M. Eimer, 1993, *Electroencephalography and Clinical Neurophysiology*, 88, pp. 414, 418. Copyright 1993 by Elsevier. Adapted with permission.

Gehring et al. (1992) that electrophysiological evidence for early selective response activation processes can be found in a priming paradigm when the precue is informative with respect to an upcoming response. However, as participants may have intentionally used this information given by the cue in preparing a response, these data cannot yet be interpreted as evidence for an automatic activation of a response that is congruent to the spatial properties of the cue. According to the model of Kornblum et al. (1990), this process should be triggered regardless of whether the precue is informative. Preliminary evidence for this was obtained in another experimental condition of the study by Eimer (1993, Experiment 1a), which was identical to the condition described above, except for the fact that the required response was not determined by the position but by the identity of the target letter. The arrow was thus not informative with respect to the upcoming response. Nevertheless, the observed LRP modulations were similar to, although somewhat smaller than, the effects described above.

The question of how these LRP effects are influenced by cue informativeness was tested in a second experiment (Eimer, 1993, Experiments 2a and 2b). The overall procedure was similar to the experiments described above. In one experimental half (Experiment 2a), the response was again dependent on the identity of the target letter, with one letter requiring a left response and the other requiring a right response. In contrast to Experiment 1a, a small percentage of no-go stimuli was included, to which a response was to be withheld. If response preparation in the cue–target interval was dependent on response-related information being conveyed by the cue, arrow direction should have no influence on the LRP waveforms in the cue–target interval. As can be seen in Figure 1b, the lateralization patterns actually found were strikingly similar to those measured with the informative cue. Participants tended to prepare the response that was indicated by the arrow's direction, although the probability that this response was correct was at chance level. In addition, the same bimodal pattern could be observed that was already present in the former experiments.

In the other experimental half (Experiment 2b), participants were instructed to respond with the left hand when a letter appeared on the right side and with the right hand when it was presented on the left side. This condition thus replicated Experiment 1b with reversed response assignments. Again the precue was predictive with regard to the upcoming reaction, as left-pointing arrows were likely to be followed by right-hand reactions and vice versa. If participants intentionally used this information to activate the expected response in the cue–target interval, an LRP pattern should have been obtained that was the reverse of the pattern shown in Figure 1a. However, this was not the case. As can be seen in Figure 1c, the initial lateralization was almost identical to the pattern found with the opposite response assignment. The LRP revealed a systematic tendency to activate the response congruent to the arrow's direction 200 ms after the cue onset, even though this response was likely to be the wrong one. However, the second phase of the LRP waveforms differed markedly from the pattern shown in Figure 1a. The initial response

activation was canceled, giving way for a reverse lateralization at the time of the target onset. Although this latter effect failed to reach statistical significance, it indicated a tendency to activate the response opposite to the direction of the arrow, that is, the response that is spatially incongruent with respect to the precue but is likely to be the correct one.

The findings from this study suggest that responses that are congruent to the direction of the arrow are activated in the interval between cue and target. Furthermore, the initial phase of this response activation seems to be independent of task instructions, as it was present even when participants were given incentive to prepare an incongruent response. The later phase of response activation seemed to be more closely related to the relationship between the direction of the arrow and the location of the expected reaction. Taken together, these findings provide evidence in favor of the dimensional overlap model: After the presentation of a spatially directed precue, a partial response activation process is automatically triggered, which may however be inhibited and then replaced by the preparation of a different response even before the presentation of the target stimulus. The experiments to be reported here were designed to further explore these effects within the same paradigm under different experimental conditions. More specifically, the question was tested whether the partial response activation processes that were found to be associated with the cue can be modified by altering response probabilities, the time interval between cue and target, and the properties of the precue.

Experiment 1: Effects of Cue Informativeness

The data from Eimer (1993) indicate that it is not necessary that the cue predicts the side of an upcoming response above chance level for systematic response activation processes to be visible in the LRP waveforms. This finding suggests that these processes may indeed be elicited independently of the participant's intentions to prepare a specific response. In Experiment 1, this hypothesis was further tested by comparing a situation in which participants were given high incentive to prepare the response congruent to the arrow's direction with a situation in which this incentive was low. Participants were instructed to respond to the target letter (*M* or *W*) only when it was correctly indicated by the precue (i.e., when the target appeared at the side where the arrow was pointed). This was the case in 75% of the trials. On half of the blocks (Experiment 1a), the response side was dependent on target identity. Given this instruction, the probability that the cue predicted the correct response was less than 50%, because the cue could be followed either by a letter requiring a left-hand or a right-hand response or by a target at the contralateral side, to which no response was to be given. In the other experimental half (Experiment 1b), the response side was determined by the location of the target, irrespective of its identity. Here the incentive to prepare the indicated response was high: When the target appeared at the cued side, the response indicated by the cue was to be produced; when it appeared

at the opposite side (in 25% of the trials), no response was to be given. If partial response activation processes in the cue–target interval are sensitive to these contingencies, the LRP waveforms should differ between experimental halves. If these processes are automatic in the sense of Kornblum et al. (1990), they should not be influenced by the difference in response instructions.

Method

Participants. Seventeen paid volunteers participated in the experiment. Eight of them were excluded because of poor eye fixation control in the cue–target interval (see below). Thus 9 participants (2 female and 7 male), ages 20–35 years (mean age = 26 years, 7 months), remained in the sample. All participants were right-handed and had normal or corrected-to-normal vision.

Stimuli and apparatus. Participants were seated in a dimly lit, electrically shielded, sound-attenuated chamber, with response buttons under their left and right hands. A computer screen was placed 100 cm in front of the participant's eyes and was carefully positioned so that the stimuli (presented white-on-gray) occurred on the participant's horizontal straight-ahead line of sight. Each trial began with a 200-ms presentation of a centrally located arrow (subtending a visual angle of $1.5^\circ \times 0.6^\circ$) pointing to either the left or the right side. Seven hundred milliseconds after cue offset, an uppercase letter (*M* or *W*) appeared for 100 ms on the left or the right side (6.0° horizontal distance from the screen center), subtending an angle of $1.0^\circ \times 1.0^\circ$. The intertrial interval between letter offset and onset of the next arrow was 2 s.

Procedure. The experiment was divided into halves (described below as Experiments 1a and 1b), each consisting of 12 blocks, resulting in a total of 24 experimental blocks. Each block consisted of 60 trials and had a duration of 2.5 min. Both letter stimuli appeared randomly and with equal probability on the left and the right side and were preceded by either a left-pointing or a right-pointing arrow. Participants had to respond to correctly indicated letters (letters presented at the side indicated by the preceding arrow) and to withhold response when the letter was incorrectly indicated by the cue. Forty-four out of 60 letters per block were indicated correctly. In Experiment 1a, participants were required to respond with the left hand to a correctly indicated *M* and with the right hand to a correctly indicated *W* (response cue–letter identity). During Experiment 1b, response was conditional on the location of the letter: Correctly indicated left letters required a left-hand reaction, whereas correctly indicated letters on the right side were to be answered by a right-hand button press regardless of letter identity (response cue–letter location). The order of experimental halves was balanced across participants. Participants were instructed to respond as quickly and as accurately as possible and to maintain central eye fixation during the trials. To make participants familiar with these specific task requirements, several training blocks were run at the beginning of the experiment.

Recording. EEG was recorded with Ag–AgCl electrodes from Fz, Cz, and Pz (according to the 10–20 system; cf. Jasper, 1958); from C3' and C4' (located 1 cm in front of C3 and C4, respectively); from PL and PR (located halfway between Pz and the ear channels); and from OL and OR (located halfway between O1 and T5, and O2 and T6, respectively).² All electrodes were referenced to the right earlobe. Horizontal electrooculogram (EOG) was recorded bipolarly from electrodes at the outer canthi of both eyes; vertical EOG was recorded from electrodes above and beside the right eye. Electrode impedance was kept below 5 k Ω . The amplifier bandpass was 0.016–70 Hz. EEG and EOG were sampled

on-line every 7 ms and were stored on disk. RTs were recorded for each trial.

Data analysis. EEG and EOG were averaged off-line for epochs of 1,800 ms, starting 100 ms prior to arrow onset and ending 100 ms after letter onset. Trials with eyeblinks, horizontal eye movements, overt response errors, or responses in no-go trials were excluded from analysis. After artifact removal, the computer-averaged horizontal EOG for each participant was scored for systematic deviations of eye position to left- or right-pointing arrows in the cue–target interval. If the maximal residual EOG deviation exceeded $\pm 1 \mu\text{V}$ (usually indicating a tendency to move the eyes in the arrow's direction), the participant was disqualified.

EEG was averaged separately for each experimental half for the four combinations of the cue correctness (correct vs. incorrect) and target position (left vs. right) variables. The LRP was computed separately for correct and incorrect cues relative to a 100-ms baseline interval prior to cue onset. To obtain the LRP, C3'–C4' difference potentials for trials with imperative stimuli occurring on the right side were subtracted from C3'–C4' difference potentials for trials with letters in the left visual field. The LRP waveforms to correct and incorrect cues were compared within 10 time windows of 100 ms duration (beginning at cue onset and ending 100 ms after letter onset) using one-tailed paired *t* tests. For the RT data, repeated measures analyses of variance (ANOVAs) were performed for the target–response compatibility (in Experiment 1a) and response side variables.

Results and Discussion

Behavioral performance. Mean RTs to correctly indicated stimuli were 501 ms (in Experiment 1a) and 277 ms (in Experiment 1b). Neither response side nor target–response compatibility (in Experiment 1a) had a significant effect on RT.

Lateralized readiness potential. As can be seen in Figure 2, the LRP waveforms in the cue–target interval revealed systematic lateralization patterns indicating that the direction of the cue was effective in triggering partial response activation processes in both Experiment 1a and Experiment 1b. When the cue correctly indicated the side of the target, participants activated a response on the side where the target was about to appear, whereas in the case of incorrect cues, the opposite response was prepared. Thus in both cases, the response indicated by the arrow's direction was activated. Similar to the lateralization patterns reported by Eimer (1993), the LRP waveforms were found to be bimodal, with a first phase of activation between 200 ms and 500 ms after the onset of the cue and a second phase from 700 ms following cue onset to beyond target onset. In Experiment 1a, the LRP waveforms to correct and incorrect cues differed significantly between 200 ms and 500 ms after cue onset and again between 700 ms after cue onset and 100 ms after target onset (see Table 1). In Experiment 1b, the LRP waveforms to correct and incorrect cues also started to differ at 200 ms after cue onset, and this difference remained significant until the 100-ms interval following the onset of the target. These differences were found to be

² In the context of this article, only the LRP waveforms that were computed on the basis of the EEG recorded from the C3' and C4' channels are analyzed and discussed.

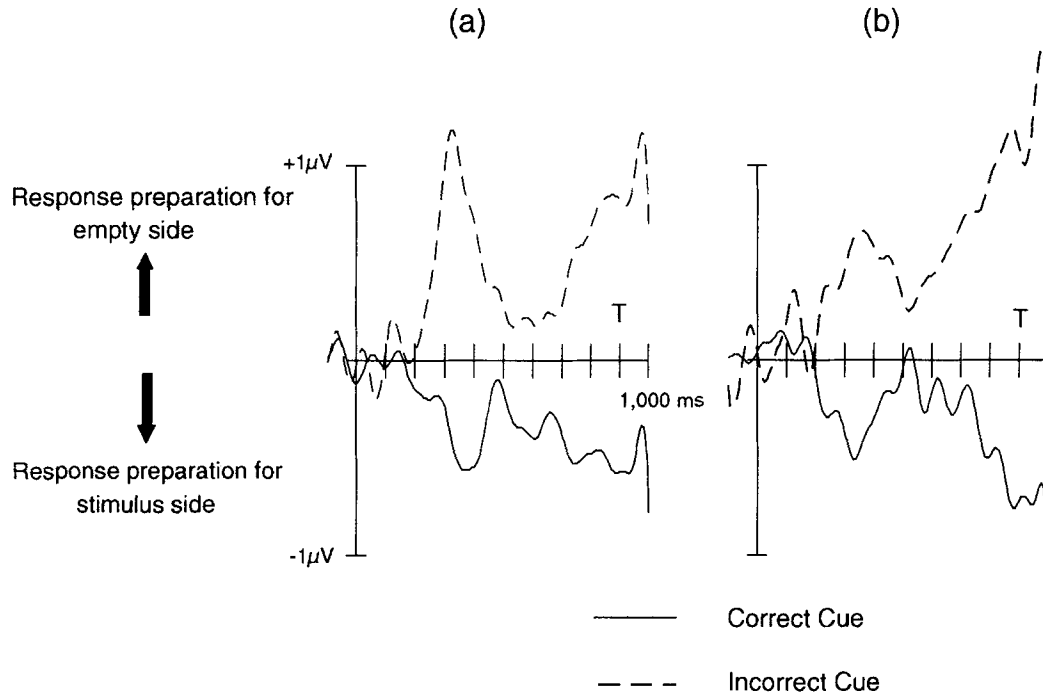


Figure 2. Experiment 1: Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for correct and incorrect cues. Panel a shows response cue-letter identity for Experiment 1a. Panel b shows response cue-letter position for Experiment 1b. Downward-directed deflections indicate a tendency to prepare a response at the stimulus's side. Upward-directed deflections indicate response preparation for the empty side. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.)

smallest in the interval between 500 ms and 600 ms after cue onset (see Table 1).

The RTs recorded in Experiment 1a were almost twice as long as the RTs obtained in Experiment 1b. As the experimental halves differed both with respect to the response information conveyed by the precue and in whether target identity or target position determined the response, it is unclear whether these RT differences are to be attributed primarily to differential response preparation processes elicited by the cue or to different processing requirements with respect to the target stimuli. To test whether the differences in cue informativeness between Experiments 1a and 1b had any influence on partial response activation, the LRP difference values obtained in Experiment 1a and in Experiment 1b within each 100-ms time window were compared using paired *t* tests. No significant difference between experimental halves was found within any time window. It may thus be concluded that differential response activation processes as evidenced by the LRP cannot account for the RT differences between Experiments 1a and 1b. The finding that in spite of the different task requirements, the LRP waveforms did not differ between experimental halves may be interpreted as evidence that the underlying processes are to be regarded as at least partially automatic. Given this interpretation, the RT differences between Experiments 1a and 1b have to be attributed to differences in target processing requirements: In the former case, the target had to be

identified on the basis of single features to determine the correct response, whereas in the latter case, target localization was sufficient for response selection.

The results from this experiment indicate that a response congruent to the arrow's direction was activated in the cue-target interval regardless of whether participants had an objective reason to prepare this response. Moreover, both the first and the second lateralization phase visible in the LRP turned out to be equally independent from the difference in response assignments that were given in Experiments 1a and 1b. Although Eimer (1993) found a reversal of the initially activated response in a situation in which the incongruent response was more likely, Experiment 1a showed that when congruent and incongruent responses are equally likely, the response tendency initially triggered by the spatial properties of the cue remains until the presentation of the target. Although the later lateralization phase may be at least partially controlled by specific response assignments (cf. Eimer, 1993), the response activation measured shortly before the onset of the target is still influenced by the spatial properties of the cue.

Experiment 2: Effects of Response Probability

The question to what extent the lateralization observed in the LRP waveforms can be influenced by the probability

Table 1
Average Mean Amplitude Differences (in Microvolts $\pm$ Standard Error) of the Lateralized Readiness Potential Waveforms to Correct and Incorrect Cues Within Consecutive 100-Millisecond Time Windows for Experiments 1a and 1b

Time window (ms postcue)	Correct-incorrect	
	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)
Experiment 1a		
0-100	0.021 $\pm$.102	<i>ns</i>
100-200	0.156 $\pm$.135	<i>ns</i>
200-300	0.728 $\pm$.244	.009
300-400	1.523 $\pm$.275	.001
400-500	0.704 $\pm$.231	.008
500-600	0.585 $\pm$.320	.053
600-700	0.631 $\pm$.373	.065
700-800	1.105 $\pm$.504	.030
800-900	1.382 $\pm$.591	.024
900-1,000	1.480 $\pm$.776	.047
Experiment 1b		
0-100	-0.570 $\pm$.088	<i>ns</i>
100-200	0.161 $\pm$.229	<i>ns</i>
200-300	0.702 $\pm$.195	.004
300-400	1.115 $\pm$.229	.001
400-500	0.675 $\pm$.216	.007
500-600	0.491 $\pm$.228	.032
600-700	0.838 $\pm$.307	.013
700-800	1.210 $\pm$.378	.007
800-900	1.779 $\pm$.462	.003
900-1,000	2.114 $\pm$.518	.002

that the indicated response has to be executed was further pursued in another experiment. Here the incentive for participants to prepare the response indicated by the precue was further reduced by including a high percentage (75%) of nontarget letters to which a response was to be withheld. Target letters were presented on 25% of all trials and required a response when they appeared at the side indicated by the precue. This was the case in 20% of all trials. As the response side was again conditional on target identity and the direction of the cue was not informative with respect to the identity of the target, the overall probability that a response was to be produced at the side indicated by the cue was only 10%. In 10% of the trials, a response was to be given at the contralateral side. The aim of the experiment was to test whether under these conditions of low response probability, the LRP still revealed evidence for the activation of responses congruent to the direction of the cue.

Method

Participants. Eight paid volunteers (2 female and 6 male), ages 20-35 years (mean age = 25 years, 4 months), participated in the experiment. All participants were right-handed and had normal or corrected-to-normal vision.

Stimuli, apparatus, procedure, and data analysis. These were similar to those in Experiment 1. In addition to *M* and *W*, a third letter (an uppercase *N*) was used as a stimulus. Participants were instructed to react to *Ws* and *Ns* (target letters) that appeared at the

position indicated by the cue. No response was to be given to incorrectly indicated target letters and to the letter *M* (nontarget letter). Twelve experimental blocks were run, with each block consisting of 60 trials. A nontarget letter was presented on 44 trials. Its position was correctly indicated by the cue on 32 trials and was incorrectly indicated by the cue on 12 trials. On the remaining 16 trials, a target letter was presented. It was correctly indicated by the cue (and thus required a response) on 12 trials and was incorrectly indicated by the cue on 4 trials. The response to correctly indicated target letters depended on letter identity: The letter *W* required a left-hand response, and the letter *N* required a right-hand response. LRP results are reported only for those trials in which a nontarget letter was presented and no overt response was recorded.

Results and Discussion

Behavioral performance. Mean RT to correctly indicated stimuli was 558 ms. Neither the side on which the response was to be given nor target-response compatibility had an effect on RTs.

Lateralized readiness potential. Again the LRP waveforms were found to be influenced by the direction of the precue, indicating a tendency to prepare a congruent response in the cue-target interval (see Figure 3). As before, the LRP waveforms were found to be bimodal, possibly reflecting two distinct response activation phases. This was further substantiated by statistical analyses that showed that the LRP waveforms for correct and incorrect cues differed significantly from 100 ms to 400 ms after cue onset and again in the postcue intervals 700-800 ms and 900-1,000 ms (see Table 2). The correct-incorrect difference in the 800-900-ms time window only approached significance.

To test whether differences in response probability influence LRP modulations in the cue-target interval, the LRP amplitude values obtained in this experiment within each time window were compared separately with the effects measured in Experiment 1a and in Experiment 1b by using multivariate analyses of variance (MANOVAs) with cue correctness as a within-subjects variable and experiment as a between-subjects variable. In both cases, the interactions between these two variables failed to approach significance within any time window.

These results show that the tendency to activate a response congruent to the arrow's direction is largely unaffected by the objective probabilities that this response will have to be executed. Although this probability was only 10% in this experiment, the LRP waveforms did not differ from the LRPs found when the precue indicated the correct response on 38% (Experiment 1a) or on 75% (Experiment 1b) of the trials. The first lateralization phase seemed to be totally unaffected by the variation in response probabilities. It may thus indeed reflect an automatic response activation process of the kind envisaged in the model of Kornblum et al. (1990). However, although this effect failed to reach significance, the differences in the LRP waveforms between correct and incorrect cues found in this experiment tended to be somewhat smaller during the second lateralization phase than in the previous experiments, which may possibly reflect the fact that the probability of executing the indicated

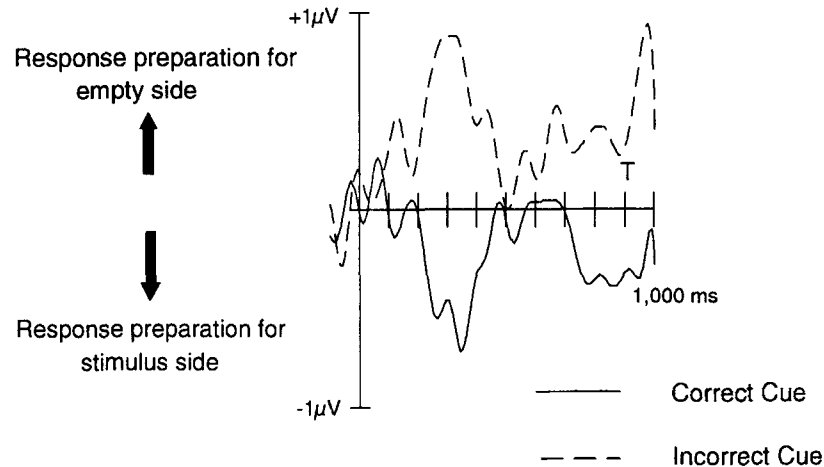


Figure 3. Experiment 2: Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for correct and incorrect cues. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.)

response was low. Given this observation, one may tentatively assume that this second phase is under the control of both the spatial properties of the cue and the objective cue-response contingencies.

Experiment 3: Effects of Cue-Target Stimulus Onset Asynchrony

In Experiments 1 and 2, response-related negative lateralizations over the motor cortex were measured when a fixed cue-target SOA of 900 ms was used. During this time interval, highly consistent LRP patterns were obtained in spite of the differences in experimental instructions. These patterns were interpreted as evidence for the existence of selective response preparation processes in the cue-target interval. However, these processes may be influenced by the

length of the cue-target interval. Investigating the relationship between cue-target SOA and partial response activation as evidenced by the LRP may lead to further insights into the timing and functional properties of these processes. A first empirical test of the influence of cue-target SOA on the LRP waveforms was conducted in the present experiment. The 700-ms interval between cue offset and target onset was replaced by an interval of 400 ms. According to the model of Kornblum et al. (1990), this manipulation should not affect the initial automatic response activation process. However, this cue-target interval may be too short for the second lateralization phase (that was found to start about 700 ms following cue offset in the previous experiments) to develop. In this experiment, responses were required to both correctly and incorrectly indicated targets and were dependent on target identity. Thus, the cue was not informative with respect to the next response. Except for the reduced cue-target interval, this procedure was identical to the experiment by Eimer (1993, Experiment 1a) that was referred to in the introduction.

Method

Participants. Fifteen paid volunteers participated in the experiment. Three of them had to be excluded because of poor eye fixation control in the cue-target interval. Thus, 12 participants (6 female and 6 male), ages 20–33 years (mean age = 24 years, 3 months), remained in the sample. All participants were right-handed and had normal or corrected-to-normal vision.

Stimuli, apparatus, procedure, and data analysis. These were identical to those in Experiment 1a, except that the cue-target SOA was 600 ms instead of 900 ms and responses were required to correctly as well as to incorrectly indicated letters.

Results and Discussion

Behavioral performance. Both cue correctness and target-response compatibility had a significant effect on

Table 2
Average Mean Amplitude Differences (in Microvolts $\pm$ Standard Error) of the Lateralized Readiness Potential Waveforms to Correct and Incorrect Cues Within Consecutive 100-Millisecond Time Windows for Experiment 2

Time window (ms postcue)	Correct-incorrect	
	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)
0–100	0.001 $\pm$.144	<i>ns</i>
100–200	0.378 $\pm$.171	.031
200–300	1.150 $\pm$.291	.003
300–400	1.188 $\pm$.374	.008
400–500	0.412 $\pm$.347	<i>ns</i>
500–600	0.219 $\pm$.338	<i>ns</i>
600–700	0.388 $\pm$.321	<i>ns</i>
700–800	0.650 $\pm$.340	.049
800–900	0.699 $\pm$.482	.096
900–1,000	0.964 $\pm$.438	.032

RTs: $F(1, 11) = 13.90$, $p < .003$, and $F(1, 11) = 7.74$, $p < .018$, respectively. The mean RTs for correctly and incorrectly indicated targets were 510 ms and 522 ms, respectively. The latencies of compatible and incompatible reactions were 508 ms and 524 ms, respectively.

Lateralized readiness potential. As can be seen in Figure 4, the LRP again revealed that participants tended to activate a response that was congruent to the arrow's direction in the cue-target interval. However, the systematic bimodal lateralization pattern that was visible with the longer cue-target SOA was missing, and the modulations of the LRP waveforms due to the direction of the precue were generally smaller than in the previous experiments. The only significant difference between the LRP waveforms to correct and incorrect cue trials was found in the 400–500-ms interval following cue onset, and the difference in the 200–300-ms time window approached significance (see Table 3). This suggests that although an early preparation of a congruent response was present, this process was possibly activated to a lesser degree than it was in the previous experiments when the interval between cue and target was longer. To test this formally, the LRP amplitude values within each time window obtained in this experiment were compared with the values measured in Experiment 1a by using MANOVAs with cue correctness as a within-subjects variable and experiment as a between-subjects variable. In the 300–400-ms time interval, the interaction between these two variables was significant, $F(1, 19) = 8.74$, $p < .008$, indicating that amplitude differences were larger in Experiment 1a than in this experiment.

On this basis of this finding, the hypothesis may be questioned that response activation processes triggered by the cue are strongly automatic in the sense of not being influenced by the specific circumstances of the experimental situation. However, in addition to the shortened cue-target SOA, this experiment differed from the studies reported above in that responses were required to both correctly and incorrectly indicated targets. This fact may

Table 3

Average Mean Amplitude Differences (in Microvolts $\pm$ Standard Error) of the Lateralized Readiness Potential Waveforms to Correct and Incorrect Cues Within Consecutive 100-Millisecond Time Windows for Experiment 3

Time window (ms postcue)	Correct-incorrect	
	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)
0–100	$0.051 \pm .182$	<i>ns</i>
100–200	$-0.160 \pm .177$	<i>ns</i>
200–300	$0.434 \pm .293$	.084
300–400	$0.345 \pm .277$	<i>ns</i>
400–500	$0.378 \pm .201$	.043
500–600	$0.379 \pm .341$	<i>ns</i>
600–700	$0.233 \pm .371$	<i>ns</i>

also have contributed to the reduction of LRP effects. Therefore, additional MANOVAs were performed to compare the LRP effects observed in this experiment with the results obtained in the study by Eimer (1993, Experiment 1a), in which the response instructions were identical, but the cue-target SOA was 900 ms instead of 600 ms. No significant interactions were found, indicating that the LRP modulations were not different in these two experiments.

On the basis of these results, it cannot finally be decided whether cue-target SOA affects the pattern of LRP modulations observed between cue and target. More systematic investigations of the relationship between cue-target SOAs, specific response assignments, and the characteristics of partial response activation processes are needed before any firm conclusion can be drawn.

Experiment 4: Including a Neutral Cue

The previous experiments have shown that after the presentation of a spatially directed precue, an initial activation

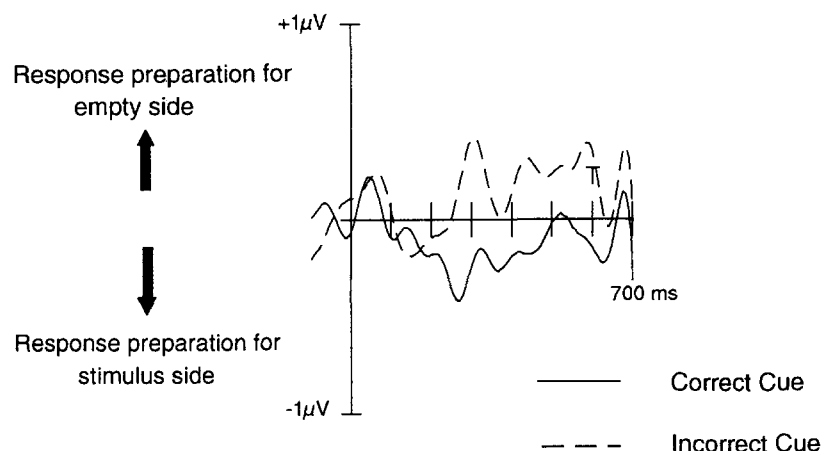


Figure 4. Experiment 3: Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for correct and incorrect cues. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.)

of a congruent response is found that can be regarded as automatic and that response activation in the cue-target interval may consist of a second phase that can be affected by task instructions. In Experiments 4 and 5, this was further tested by varying the properties of the precue. In Experiment 4, a neutral cue condition was included, in which a spatially ambiguous precue (a double arrow) was presented prior to the occurrence of the target. This neutral cue was followed by a target on the left or the right side with equal probability and was therefore not informative with regard to the position of the target or the identity of the upcoming response. On the other trials, a single arrow was presented that predicted the position of the target with 75% validity. Two target stimuli (a go and a no-go letter) appeared with equal probability. The participant's task was to press a button on the side of the stimulus whenever a go letter was presented. Given these instructions, the single arrow was moderately informative with regard to the upcoming response because it was likely that when a go stimulus was presented, it would appear at the indicated side. If the conclusions drawn from the previous experiments are correct, one would expect to find evidence for selective response activation in the LRP waveforms to the informative cue and no systematic lateralization pattern in the LRPs to the double arrow.

Method

Participants. Ten paid volunteers participated in the experiment. Two of them had to be excluded because of poor eye fixation control in the cue-target interval. Thus, 8 participants (4 female and 4 male), ages 24–40 years (mean age = 27 years, 8 months),

remained in the sample. All participants were right-handed and had normal or corrected-to-normal vision.

Stimuli, apparatus, procedure, and data analysis. These were similar to those in Experiment 1. The experiment consisted of 12 experimental blocks, and the uppercase letters *M* and *W* were used as imperative stimuli. On 48 out of 60 trials per block, a single arrow was presented. It was followed by a letter stimulus at the indicated side on 36 trials (correctly indicated letters) and at the contralateral side on 12 trials (incorrectly indicated letters). On the remaining 12 trials, a double arrow was presented, which was followed by a letter stimulus at the left or the right side with equal probability (neutral trials). The participants were instructed to respond to the letter *M* (go stimulus) and to withhold response when a *W* was presented (no-go stimulus). Responses were contingent on the position of the go stimulus: A left-hand response was required to an *M* presented on the left side, and a right-hand response was required to an *M* presented on the right side.

Results and Discussion

Behavioral performance. Cue correctness had a significant influence on RTs, $F(2, 14) = 16.01, p < .001$. Mean RTs for correctly indicated targets, incorrectly indicated targets, and neutral trials were 394 ms, 419 ms, and 404 ms, respectively. Pairwise comparisons using paired *t* tests revealed that RTs were significantly different between each of these conditions.

Lateralized readiness potential. When the precue was informative, the LRP waveforms again revealed the bimodal lateralization pattern that is already familiar from the previous experiments (see Figure 5). Starting about 200 ms following cue onset, an initial activation of the response indicated by the cue can be seen in the LRP waveforms. In

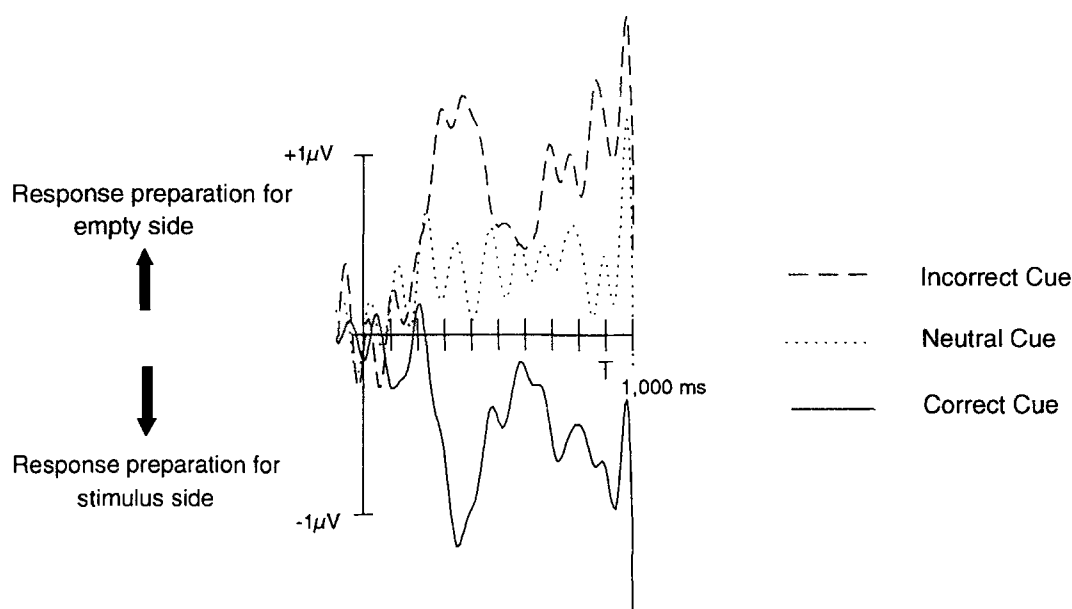


Figure 5. Experiment 4: Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for correct, neutral, and incorrect cues. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.)

the middle period of the cue–target interval, these lateralizations became smaller but were found to increase again about 300 ms before target onset. The LRP waveforms to correct and incorrect cues started to differ significantly 200 ms following cue onset, and this difference remained significant for the rest of the cue–target interval until the 100-ms time window following target onset (see Table 4). In contrast to the LRP waveforms elicited by the informative cue, the LRP to the double arrow did not reveal the existence of systematic response activation processes (see Figure 5). As expected, it remained close to the baseline throughout the cue–target interval and did not show any indication of bimodality. To test whether the LRP waveforms to neutral cues differed from those found in response to correct and incorrect cues, they were pairwise compared within each 100-ms time window by using one-tailed paired *t* tests. The LRPs for correct cues and for neutral cues were found to be different from 200 ms after cue onset to 100 ms after the presentation of the target (see Table 4). When the waveforms for neutral cues were compared with the LRPs to incorrect cues, differences in the expected direction were found within each of these time windows, although these differences reached significance only in the 200–300-ms time window and approached significance in the 300–400-ms and 800–900-ms intervals following cue onset (see Table 4).³

Experiment 5: Using a Nonspatial Precue

In Experiments 1–4, converging evidence has been collected in favor of the assumption that an activation of left or right responses can be triggered automatically in a priming paradigm by the presentation of an arrow cue pointing to the left or the right side. What remains to be demonstrated, however, is the inherent dependency of this process on the fact that spatial attributes are shared between cues and responses. According to the dimensional overlap model proposed by Kornblum et al. (1990), automatic response activation processes are to be expected only when S-R pairings correspond with respect to specific properties. In the context of the present paradigm, such processes should therefore not be triggered when precues are not characterized by a spatial attribute. However, if these cues are predictive with respect to the upcoming response, controlled response identification processes may nevertheless be activated, as these processes are supposed to be governed by specific cue–response contingencies.

To test these hypotheses, cues without inherent spatial properties (centrally presented red or blue squares) were used in this final experiment. Red and blue circles presented on the left or the right side of the screen served as target stimuli. Responses were dependent on the identity of the target, as a red target was paired with a left-hand response and a blue target was paired with a right-hand response. To maximize the incentive to prepare a specific response in the cue–target interval, the cue was made predictive of both the location of an upcoming target stimulus and the response to be produced. When a red cue was presented, the probability

was 75% that the target stimulus was red and 75% that the target stimulus would be presented on the left side. A blue cue indicated with 75% validity the appearance of a blue target stimulus and the presentation of a target on the right side. As the color of the cue was predictive with respect to the target color, this information may be used to activate the expected response in the cue–target interval. However, although the cues did not differ with respect to any spatial attribute, responses were still characterized by their spatial location. In the absence of any dimensional overlap between cues and responses, no early automatic response activation should be elicited by the precues.

Method

Participants. Eleven paid volunteers participated in the experiment. One of them had to be excluded because of poor eye fixation control in the cue–target interval. Thus, 10 participants (8 female and 2 male), ages 21–34 years (mean age = 26 years, 2 months), remained in the sample. All participants were right-handed and had normal or corrected-to-normal vision.

Stimuli, apparatus, procedure, and data analysis. These were similar to those in Experiment 1, except that different cue and target stimuli were used. Red and blue squares (subtending $1.0^\circ \times 1.0^\circ$ visual angle) that were presented with equal probability at the center of the screen served as precues. Target stimuli were red and blue circles with a diameter of 1.1° visual angle that were presented on the left or the right side (6.0° horizontal distance from the screen center). The experiment consisted of 12 experimental blocks. On 18 out of 60 trials per block, a red cue was followed by a red target stimulus on the left side. On another 18 trials, a blue cue was followed by a blue target stimulus on the right side. The remaining six cue–target combinations (red cue–red target right, red cue–blue target left, red cue–blue target right, blue cue–red target left, blue cue–red target right, and blue cue–blue target left) were presented four times per block, respectively. Given these probabilities, the color of the cue was informative with regard to both the color and the position of the upcoming target stimulus. On 44 out of 60 trials, a cue was followed by a target of the same color. Red cues were followed by left targets on 22 trials and by right targets on 8 trials. Blue cues were followed by right targets on 22 trials and by left targets on 8 trials. Participants were instructed to press a response button on the left side when a red target was presented and a response button on the right side when the target was blue. Cues could thus be characterized as correct or incorrect with respect to both the color and the position of the target stimulus. They were characterized as correct with respect to

³ The finding that the neutral–incorrect comparisons yielded less significant results than the correct–incorrect and correct–neutral comparisons may be due to the fact that an unequal amount of trials entered into the averaged waveforms for correct, incorrect, and neutral cues, because during each experimental block, 36 correct cues but only 12 neutral and incorrect cues were presented. This presumably led to a lower signal-to-noise ratio in the averaged waveforms for incorrect and neutral cues as compared with correct cues, resulting in a higher variance in the individual LRP waveforms. As the number of participants was small, this may be responsible for the fact that although the differences between the neutral and the incorrect cue condition were clearly visible in Figure 5, some of the neutral–incorrect comparisons failed to reach statistical significance.

Table 4

Average Mean Amplitude Differences (in Microvolts $\pm$ Standard Error) of the Lateralized Readiness Potential Waveforms to Correct, Neutral, and Incorrect Cues Within Consecutive 100-Millisecond Time Windows for Experiment 4

Time window (ms postcue)	Correct-incorrect		Correct-neutral		Neutral-incorrect	
	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)
0-100	0.030 $\pm$.169	<i>ns</i>	0.102 $\pm$.204	<i>ns</i>	0.072 $\pm$.214	<i>ns</i>
100-200	0.357 $\pm$.191	.052	0.335 $\pm$.197	.067	0.022 $\pm$.207	<i>ns</i>
200-300	1.324 $\pm$.273	.001	0.762 $\pm$.141	.001	0.562 $\pm$.276	.041
300-400	2.260 $\pm$.387	.001	1.347 $\pm$.223	.001	0.913 $\pm$.517	.061
400-500	1.458 $\pm$.338	.002	0.961 $\pm$.169	.001	0.497 $\pm$.426	<i>ns</i>
500-600	0.856 $\pm$.432	.044	0.652 $\pm$.188	.005	0.204 $\pm$.549	<i>ns</i>
600-700	1.233 $\pm$.505	.023	0.760 $\pm$.240	.008	0.473 $\pm$.449	<i>ns</i>
700-800	1.460 $\pm$.542	.016	1.054 $\pm$.263	.003	0.406 $\pm$.493	<i>ns</i>
800-900	1.848 $\pm$.638	.012	0.987 $\pm$.233	.002	0.861 $\pm$.566	.086
900-1,000	2.034 $\pm$.631	.008	1.305 $\pm$.352	.004	0.729 $\pm$.528	<i>ns</i>

target color when the target color matched the color of the cue and as incorrect with respect to color when its color was different. They were characterized as spatially correct when the target was presented at the position predicted by the cue (red cue-left target and blue cue-right target) and as spatially incorrect when it appeared at the opposite side. As in Experiments 1-4, the LRP waveforms elicited by spatially correct cues were compared with the LRPs elicited by spatially incorrect cues.

Results and Discussion

Behavioral performance. Mean RTs to targets at correctly and incorrectly indicated positions were 363 ms and 394 ms, respectively, $F(1, 9) = 23.01$, $p < .001$. When the target color was correctly indicated, mean RT was 357 ms, as compared with 400 ms when the target color differed from the color of the cue, $F(1, 9) = 42.46$, $p < .001$. A highly significant interaction between these effects of spatial and color correctness, $F(2, 18) = 160.06$, $p < .001$, indicated that these were mainly due to the fact that RTs were fastest in the condition when both the position and the color of the target were correctly indicated by the cue. Here, mean RT was 306 ms, as compared with a mean RT of 403 ms for all other conditions. When the target position was compatible with the required response, the mean RT was 343 ms, as compared with 414 ms when the target-response pairing was incompatible, $F(1, 9) = 54.22$, $p < .001$.

Lateralized readiness potential. As can be seen in Figure 6, the results obtained in this experiment were quite clear-cut. In contrast to all previously reported experiments, no indication of a systematic lateralization was found in the LRP waveforms to spatially correct and incorrect cues before 600 ms following the onset of the cue. Between 600 ms and 700 ms after cue onset, the difference between these LRP waveforms approached significance. From 700 ms following cue onset onward, the LRP waveforms revealed significant lateralization differences for spatially correct and incorrect cues, thus indicating a selective activation of the response side that was indicated by the color of the precue (see Table 5). The onset of this response activation paral-

leled the onset time of the second lateralization phase that was observed in the previous experiments.

Two conclusions may be drawn from the results: First, the assumption was confirmed that no early automatic response activation process is triggered by a precue in the absence of dimensional overlap, where responses are characterized spatially, but the cues lack any discriminating spatial feature. Whereas in the previous experiments, systematic modulations of the LRP waveforms started about 200 ms after cue onset, these early effects were completely absent in this experiment. This negative finding is remarkable, because the cues were predictive with respect to the upcoming response. In the experiments reported above, early response activation processes were visible even when the cues did not convey any response-related information. Furthermore, a response activation process was evidently elicited about 200 ms prior to the onset of the target. This process may be regarded as intentionally controlled, because it was dependent on the specific and quite artificial pairings between the color of the cue and the side of the expected response that were constituted by the experimental instructions. This latter activation process may thus be the outcome of a response identification process of the type postulated in the model of Kornblum et al. (1990).

General Discussion

The concept of S-R compatibility refers to the fact that in tasks in which stimuli and responses share certain attributes, the performance of participants is influenced by the way that stimuli and responses are paired with each other. When specific S-R pairings are equivalent with respect to a given attribute, performance benefits are likely to be observed, whereas in the opposite case, performance costs will result. According to the model of Kornblum et al. (1990), these S-R compatibility effects are due to the fact that in the presence of dimensional overlap, specific responses are automatically activated after the presentation of a stimulus. In the case of congruent S-R pairings, the activated re-

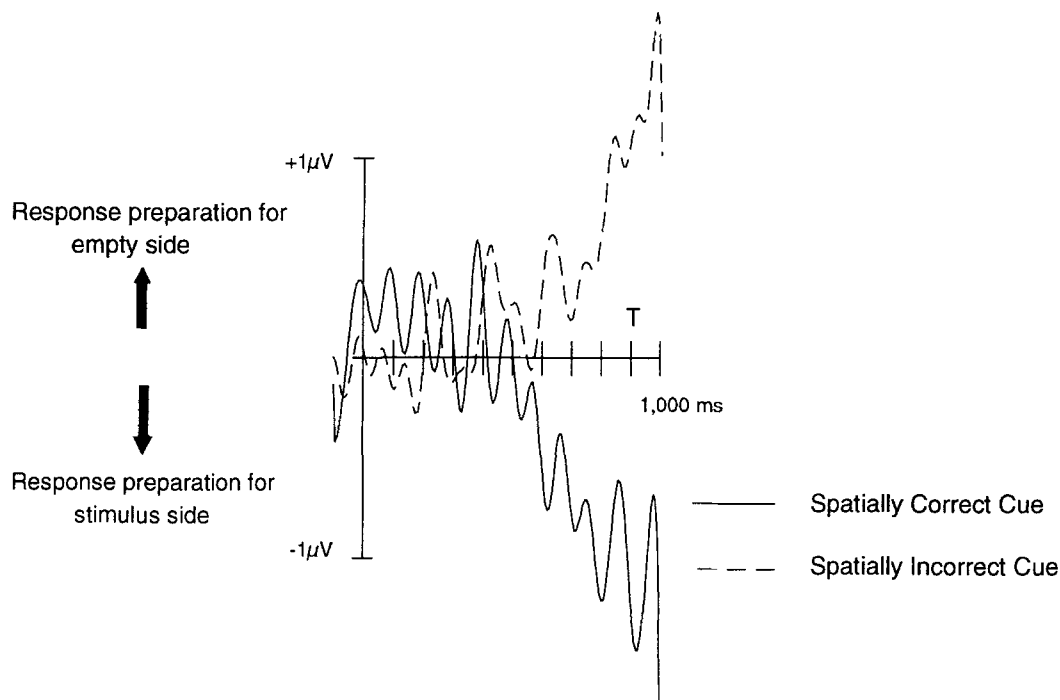


Figure 6. Experiment 5: Grand mean lateralized readiness potential waveforms recorded in the interval between cue onset and 100 ms after target onset (T) for spatially correct and spatially incorrect cues. (Waveforms are low-pass filtered with a cutoff frequency of 12 Hz and 24 dB/octave roll-off.)

sponses are the correct ones and can be executed without further delay. In the case of incongruent pairings, this initial response activation must be replaced by the activation of the correct response that is determined in the course of a controlled response identification process.

In the experiments reported here, electrophysiological evidence for the existence of these processes was collected in a number of priming experiments. By measuring the LRP

in the cue–target interval as an indicator of partial response activation, it was studied whether left or right responses are activated by spatially directed precues. In accordance with the dimensional overlap model, it was found that such responses are activated as early as 200 ms after cue onset. They were triggered independently of the informativeness of the cue with respect to the response required by the upcoming target stimulus, as an activation of congruent responses was observed when the probability was at chance level that the indicated side was the response side and even when it was likely that the required response was at the contralateral side. This independence from task instructions and subjective expectancies suggests that the initial response activation process may be automatic, as was proposed by Kornblum et al. (1990). Moreover, this process seems to be critically dependent on the existence of dimensional overlap between cues and targets. When the arrow cues were replaced by red and blue squares, no early response activation process was elicited, although these cues were informative with respect to the upcoming reaction. This finding supports the assumption of the dimensional overlap model that no automatic response activation will be elicited in the absence of dimensional overlap.

Following the initial activation of a congruent response, a second response activation phase was observed that started about 600–700 ms after cue onset and that was at least partially influenced by specific task instructions and subjective expectancies. When the expected response was con-

Table 5
Average Mean Amplitude Differences (in Microvolts $\pm$ Standard Error) of the Lateralized Readiness Potential Waveforms to Spatially Correct and Spatially Incorrect Cues Within Consecutive 100-Millisecond Time Windows for Experiment 5

Time window (ms postcue)	Correct–incorrect	
	($\mu\text{V} \pm \text{SE}$)	<i>p</i> (one-tailed)
0–100	$-0.330 \pm .237$	<i>ns</i>
100–200	$-0.280 \pm .352$	<i>ns</i>
200–300	$0.023 \pm .451$	<i>ns</i>
300–400	$-0.100 \pm .619$	<i>ns</i>
400–500	$0.506 \pm .578$	<i>ns</i>
500–600	$0.474 \pm .708$	<i>ns</i>
600–700	$1.086 \pm .770$	.096
700–800	$1.417 \pm .690$	.035
800–900	$1.977 \pm .557$	.003
900–1,000	$2.596 \pm .541$	.001

tralateral to the direction of the arrow, this response tended to be prepared within this later phase (Eimer, 1993, Experiment 2b). When the probability that the indicated response was to be executed was low, LRP modulations tended to be smaller in this later phase than when under conditions of high response probability. When red and blue squares were used instead of left- or right-pointing arrows and no early response activation could be observed, the response indicated by the color of the cue was strongly activated during this later phase.

These findings are in agreement with the results of the experiments by Gehring et al. (1992). In Gehring et al.'s study, the cue-target SOA was 1,000 ms, and centrally presented letter stimuli were used as precues that were either identical to the target letter on 80% of the trials or uninformative with regard to the identity of the target. As these precues had no inherent spatial characteristics, no early automatic response activation was expected. Evidence for a later, presumably controlled response activation in the cue-target interval should be found only when the cue was predictive with regard to the future reaction. The data from Gehring et al. confirmed these predictions: No selective response activation was evident in the LRP waveforms with uninformative cues, and an activation of the indicated response was present only toward the end of the cue-target interval when the precue was informative.

Automatic and Controlled Response Activation

Given the aforementioned results, it is tempting to relate the initial and late response activation phases that were revealed in the LRP waveforms directly to the automatic and controlled activation processes that have been postulated by Kornblum et al. (1990). However, this may be premature for a number of reasons. First, the degree to which the initial response activation process is initiated may depend on specific experimental circumstances like the length of the cue-target SOA (Experiment 3). If this process was automatic in a strong sense, it should not be influenced by the cue-target SOA as long as this interval is long enough for pretarget response activation processes to be elicited at all. Further research using both long and short cue-target SOAs is necessary to determine the relationship of time separating cue and target and the timing and morphology of the LRP modulations that possibly reflect different stages of response activation. Second, although the direction of the arrow precues may be quite easy to determine, they can still be regarded as conveying spatial information in a symbolic form. Therefore, some form of interpretation of the cue is necessary on the side of the participants before the initial response activation process can be triggered.⁴ This may in turn require that attention has to be focused on the cue and that the extent to which this process is elicited depends on the amount of attention directed toward the cue. In the experiments reported here, the cue was always informative with respect to the location of the target and thus most likely had been attended to by the participants. However, it seems possible that when partici-

pants do not attend to the cue (i.e., because they choose to ignore it or are instructed to attend elsewhere), no initial response activation will be elicited. If this was the case, the early response activation process could not be regarded as strongly automatic but rather as partially automatic in the sense that it may be facilitated or attenuated by attention. However, given the concept of automaticity used by Kornblum et al. (1990, p. 261), this process may be characterized as partially automatic if it can be shown that it cannot be completely suppressed voluntarily. The data from the present experiments clearly support this assumption. Furthermore, it seems obvious that the later response activation phase is not completely under the control of the objective cue-response contingencies. Otherwise, this phase should have been absent when the cue was uninformative with respect to the future response, because in this situation, participants should await the presentation of the target stimulus to determine the correct response. As this was not the case, it seems that the processes responsible for the LRP modulations toward the end of the cue-target interval are not completely controlled by the participant's intentions.

Attentional Orienting in the Cue-Target Interval

Another problem to be discussed concerns the question of whether the LRP modulations found in the cue-target interval can be regarded as direct evidence for motor response activation triggered by the cue. In the introduction, a number of empirical studies were cited that provided evidence in favor of direct links between the LRP and selective motor preparation. However, the precue was always predictive with regard to target location in the present experiments, presumably resulting in a shift of spatial attention toward the indicated side (cf. Posner, 1980). Therefore, the possibility cannot be simply ruled out that the lateralizations found in the cue-target interval are an indication of covert attentional orienting or even overt eye movements in the direction indicated by the cue rather than motor preparation. Because the criteria for detecting and rejecting horizontal eye movement used in the present experiments were very strict, the possibility that eye movements in the cue-target interval are responsible for these effects can be ruled out. However, in studies that investigated the effects of covert attentional orienting on event-related potential waveforms in a precuing paradigm (Harter & Anllo-Vento, 1991; Harter, Miller, Price, LaLonde, & Keyes, 1989), systematic lateralizations following the presentation of arrow cues have also been reported. Harter and Anllo-Vento (1991) and Harter et al. (1989) found an enhanced negativity at posterior scalp sites contralateral to the direction of the cue that was present between 200 ms and 500 ms after cue onset, that is, in the time range where the first lateralization phase was observed in the LRP waveforms of the present exper-

⁴ This becomes evident when one compares these cues with peripheral stimuli presented at the location where a target is expected. In this situation, information about the position of the target is given directly, which makes further interpretation of the cue unnecessary.

iments. Harter and Anllo-Vento tentatively interpreted this effect as evidence for the activation of processes associated with the orienting of visual attention in space. To test whether the LRP effects reported above are at least partially a reflection of attentional orienting processes, additional analyses were conducted on the experimental data. It was tested whether systematic negative lateralizations parallel to those recorded over the motor cortex were present and possibly even larger at lateral posterior electrodes. For all experiments, it was found that these effects were maximal over the motor areas of the brain and, if present at all, were considerably smaller over lateral parietal and occipital electrodes. Moreover, the results obtained in Experiment 5 are clear evidence against the assumption that the early LRP effects reported here are a reflection of voluntary attentional orienting. In that experiment, the early lateralization phase was completely absent, even though the color cues were informative with respect to the position of the upcoming targets and should thus have triggered an attentional orienting process. Given these results, it is very unlikely that the LRP effects reported here are primarily a reflection of covert attentional orienting.

Response Priming and Response Inhibition

It may be argued that the LRP pattern—an initial negative lateralization followed by a drop in negativity and then by a second lateralization phase—observed in the present experiments might reflect response priming as well as response inhibition processes. Evidence for the assumption that an automatic activation of a spatially congruent response may be followed by an inhibitory phase comes from the study by De Jong et al. (1994, Experiment 2). In the case of fast responses, they found RT benefits for congruent as compared with incongruent responses. For slow responses, however, congruent responses tended to be delayed relative to incongruent responses. This pattern of results may be due to an active inhibition of responses that were previously automatically activated.

In most of the present experiments, no-go trials were included. This may be an additional cause for active inhibition processes to be activated in the interval between cue and target, which may be reflected in the disappearance of the negative lateralization about 500 ms after cue onset. That go–no-go decisions may be reflected in specific LRP modulations has been demonstrated by Miller and Hackley (1992, Experiment 2). They observed the disappearance of an initial LRP elicited by no-go stimuli in a situation in which the response side was determined by an easily discriminable stimulus attribute, whereas go and no-go trials differed with respect to a more slowly discriminable feature. However, the fact that bimodal LRP patterns could be observed in situations in which no no-go trials were included (Eimer, 1993, Figure 1) indicates that there seems to be no direct connection among the presence of no-go trials, active response inhibition, and the complete LRP pattern observed in the present experiments.

If the disappearance of lateralization in the middle part of

the cue–target interval is a reflection of response inhibition processes, these processes most likely originate from different regions of the brain than does the LRP. Evidence for this comes from experiments with monkeys conducted by Sasaki and Gamba (1986) and Gamba and Sasaki (1990), who recorded intracranial field potentials during no-go trials. They found that in contrast to the LRP, brain potentials related to the decision not to move and the suppression of motor execution are located in prefrontal areas of the monkey cortex.

Automatic Response Activation and Behavioral Compatibility Effects

Another issue that deserves discussion concerns the fact that systematic effects of target–response compatibility on RTs could not be found in all of the aforementioned experiments. RT compatibility effects were present in Experiment 3 and Experiment 5 but were missing in Experiment 1a and Experiment 2.⁵ This latter finding is striking, because the LRP waveforms revealed activations of congruent responses that were clearly present until the 100-ms time interval following target onset (cf. Figures 2 and 3). Why did these processes fail to affect response latencies in these two experiments?

That an initial automatic response activation is not necessarily connected to RT benefits has already been observed by De Jong et al. (1994, Experiment 3). They found early LRP modulations indicating the selective priming of a congruent response in a condition in which this response was actually delayed as compared with incongruent reactions.⁶ With respect to the present studies, it should be noted that there is one obvious difference between the experiments in which compatibility effects were observed and the experiments in which these effects were absent. In the latter, but not the former, experiments, no-go trials were included. The observation that the inclusion of no-go trials leads to a disappearance of spatial compatibility effects on RTs confirms previous findings reported by Eimer (1993). Here two experimental conditions in which response was dependent on the identity of target letters were identical except for the fact that in one condition (Experiment 2a), 25% of the trials were no-go trials, whereas in the other condition (Experiment 1a), no no-go trials were included. A highly significant compatibility effect was found in the latter case but was completely absent in the other condition. Which functional relationships might be responsible for the disappearance of compatibility effects due to the presence of no-go trials? It is possible that the existence of no-go stimuli may lead participants to adopt a more conservative response criterion. Although this will presumably not influence automatic re-

⁵ In Experiments 1b and 4, no incompatible target–response pairings were included, so no compatibility effects on RT could be measured.

⁶ De Jong et al. (1994) explained this finding by referring to an independent conditional-response priming process that is sensitive to specific S-R pairings and may counteract the automatic response activation.

sponse activation processes, the connection between automatic response activation processes and the response execution stage (which is part of the activation function in the dimensional overlap model; see Kornblum et al., 1990, p. 257) may be inhibited when response criteria are raised. If this was the case, response latencies would depend primarily on the controlled response identification process, which would lead to a dissolution of RT benefits resulting from automatic response activation. Again, these assumptions will have to be tested in future experiments. Generally, it will have to be studied how cue-response compatibility and target-response compatibility interact in a priming paradigm to produce S-R compatibility effects. In experiments in which the cue-target interval is long, automatic response activation processes elicited by precues may have already disappeared at the time of target onset, so that compatibility effects on RT will be largely due to target-response compatibility. With shorter cue-target intervals, spatial correspondences between cue and response may have a more direct influence on overt performance.

To summarize, the present experiments have demonstrated that the LRP may be a useful tool for investigating the time course and the functional properties of partial response activation processes in priming paradigms. Converging evidence has been collected showing that congruent responses are automatically triggered by spatially directed precues shortly after cue onset and that a second response activation process can be elicited even before the occurrence of the target that is at least partially dependent on the specific S-R contingencies of an experimental task.

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