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S–R compatibility and response selection

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Abstract

In serial stage models, perception and action are usually thought to be linked to each other by an S–R translation mechanism. However, phenomena of S–R compatibility suggest a more direct relationship between perceptual and action domains. We discuss behavioral and psychophysiological evidence that irrelevant stimulus information automatically activates response codes, but then decays over time.

In a series of reaction time studies and electrophysiological experiments, we investigated both temporal and functional properties of the assumed automatic response activation process. We found that the amount of interference due to irrelevant spatial information depends upon how long its availability precedes that of the information relevant for response selection. This indicates that response activation decays rather quickly. If response-relevant and irrelevant spatial information are simultaneously available, electrophysiological measurements show that automatic activation of the spatially corresponding response rises soon after stimulus onset, but then dissipates and gets replaced by the activation of the response indicated by the relevant stimulus attribute.

We conclude that these findings do not support a pure translation account, but rather suggest the presence of two parallel and (at least partially) independent routes from perception to action: A *direct route*, allowing for automatic activation of response codes if stimulus and response features overlap, and an *indirect route* linking S and R codes in an arbitrary manner. Via the direct route responses may be primed independent of task-specific contingencies, while the correct response is selected via the indirect route. This use suggests that (a) the transmission of stimulus information to response stages does not (fully) depend on task relevance and that (b) different stimulus features can be transmitted asynchronously and independently from one another.

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1. Introduction

An abstract representation of the major functional components usually believed to underlie perception and action control is depicted in the lower part of Fig. 1. In the afferent part on the left-hand side it is shown that an external event in the environment leads to an internal stimulation pattern (in a receptor organ) which in turn generates a sensory code in the brain that represents this peripheral pattern at the central level. In the efferent part on the right-hand side the story goes top-down. It starts with a motor code in the brain which again represents a certain pattern of excitation and also has the power to activate this pattern (in an effector organ).

How could sensory codes and motor codes talk to each other in this scheme? Since the times of Descartes it is generally believed that they cannot talk to each other directly and that some *translation* is required instead. This is because sensory codes and motor codes are incommensurate in terms of contents. Sensory codes stand for patterns of stimulation in receptor organs and motor codes stand for patterns of excitation in muscles, and there is no obvious way these two entities could be compared or matched. In reaction time research the metaphor of translation has therefore become a prominent theoretical notion to account for the internal operations underlying the mapping of responses to stimuli (e.g., Massaro, 1990; Sanders, 1980; Welford, 1968).

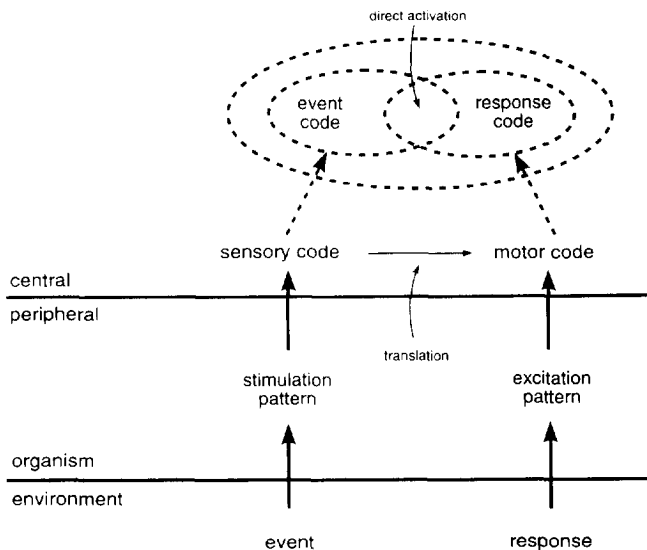


Fig. 1. Model of the relationship between perception and action. Lower part (unbroken lines): separate coding view; sensory and motor codes linked to each other by translation. Upper part (broken lines): common coding view: event codes and response codes linked to each other by direct activation, depending on their overlap in the common representational domain.

The translation metaphor stresses the incommensurability between sensory codes and motor codes. It implies that these two codes differ in contents and format and must therefore be generated in separate representational domains. On the one hand there is a sensory coding domain organized in terms of sensory dimensions, and on the other hand there is a motor coding domain organized in terms of motor dimensions. The translation metaphor bridges the gap between perception and action by creating links between incommensurate entities. Correspondingly, translation is central to all the varieties of linear stage models. In these models, stimulus-related stages come first and response-related stages come later, and the translation stage is the missing link between them.

When referring to translation as the bridging operation between sensory and motor codes it is usually assumed that this operation is a controlled process governed by the specific stimulus-to-response mappings as they are set up, for example, in experimental instructions. Such mappings could be implemented as rules that relate stimuli and responses, or stimulus and response features, and the operation of translation can be considered being the realization of such rules.

In the following we want to show that the translation framework, though it may provide a suitable framework of a large number of stimulus–response relationships, is in a way incomplete. We believe that stimulus features may affect response selection in ways that are not adequately captured by the translation model. The translation framework assumes that perception and action are two distinct domains of mental life, thereby necessitating a linking mechanism that relates the two. In contrast, we would like to promote a *common coding approach* to perception and action. This approach holds that there is a functional continuity between perception and action and that this continuity is relevant for an adequate characterization of the transition from stimuli to responses.

This is illustrated in the upper part of Fig. 1, where, above and beyond sensory and motor codes, an additional representational domain is postulated that includes *event codes* and *response codes*. Unlike sensory codes and motor codes, which belong to separate coding domains and therefore require translation, event codes and response codes share the same representational domain and are, hence, commensurate. As a consequence, particular pairings of event codes and response codes can be characterized by their degree of similarity, or overlap of features in the common representational space (cf., e.g., Kornblum et al., 1990). To the extent event codes and response codes overlap, the translation operation becomes dispensable. Instead, event codes have direct access to response codes within the same representational domain, and the directness of that access should depend on the degree of their overlap. In contrast to voluntarily controlled translation, direct response activation should be automatic in the sense that, since it relies on similarity, it occurs independently from any instruction or intention and, hence, in parallel to voluntary translation. This distinguishes our approach from models like that of Sanders (1983) and Van Duren and Sanders (1988).

In what follows we provide experimental evidence for the existence of such automatic response activation processes. We will present both behavioral and psychophysiological data from situations where stimuli and responses share spatial

properties but these similarities are irrelevant for response selection. On the basis of the translation framework, no systematic effect of such an irrelevant feature overlap is to be expected, since there is no translation process operating on the basis of spatial properties. Any effects of spatial properties shared between stimuli and responses may therefore be regarded as evidence for the presence of a response activation process that is independent of controlled S–R translation.

2. Behavioral evidence

We will first consider experiments that investigated the dynamics of response activation by using reaction time measures. The basic tasks were always of the same kind: Subjects performed a binary-choice reaction time task by pressing a left or right key in response to a particular stimulus feature such as color, form, or letter identity. Most critically, the stimulus appeared randomly to the left or right side of fixation or some reference point. As commonly known from the work of Simon and co-workers (Simon, 1969; Simon and Rudell, 1967), subjects are unable to ignore the irrelevant spatial cue provided by stimulus position: Responses are faster with spatial correspondence between stimulus and response than with noncorrespondence.

A translation account of this so-called Simon effect was first suggested by Wallace (1971): It proposes that a stimulus code is always translated into a response code and, when spatially corresponding, the translation process is facilitated by the presence of the irrelevant spatial code. Note the following strong implication of the translation account: As the presence of irrelevant spatial stimulus information is assumed to affect S–R translation, it should be possible to eliminate its effects if presented after the completion of the translation process.

Accordingly, Hommel (1995a) provided in each trial fully valid information about the next response, so that subjects could complete the S–R translation in advance. They had about 1 s to prepare the response, followed by a green Go or red No-go signal, appearing randomly on either the left or right side. With a Go signal, subjects responded as fast as possible. Note that there was no need to “translate” the Go signal into a response code, as the response could be prepared in advance. Instead, the Go signal only served as a timing signal. Thus, according to the translation approach, the location of the Go signal should not matter. Nevertheless, reaction time was much faster with spatial correspondence between the Go signal and the response key, which is inconsistent with the idea that irrelevant S–R correspondence affects S–R translation.

A possible objection would be that subjects may have been reluctant to really complete S–R translation before the Go signal came up, because this would have paid for them in only 50% of the trials. So, Hommel (1995b) ran a replication using a true simple reaction task. That is, there was no No-go signal, and the to-be-prepared response was always executed as soon as the Go signal appeared. On average, responses were about 100 ms faster than with 50% Go trials, indicating that response preparation was indeed much more efficient. However, the same

kind of correspondence effect was obtained, thus ruling out the incomplete-preparation argument.

So, irrelevant spatial stimulus information seems to affect response selection even if an effect on S–R translation is precluded by the experimental design. This suggests that translation is not the only way to reach the response selection stage and to activate response codes. Rather, it seems that even irrelevant stimuli activate response codes in an automatic fashion, provided that there is some feature overlap between stimulus and response (in the sense of Kornblum et al., 1990) and that the response has not yet been emitted. This is consistent with automatic activation models, but not with pure translation accounts.

It is obvious that automatic activation cannot be sufficient to actually launch the respective response, because this would produce 100% errors in case of S–R non-correspondence. Instead, the final response selection should await the processing of the relevant stimulus feature. As Kornblum et al. (1990) or De Jong et al. (1994) have noted, this suggests that there are two processes running parallel: a controlled translation of the relevant stimulus into the correct response and an automatic activation of the same or an alternative response by irrelevant stimulus position.

That is, relevant and irrelevant stimulus features may be processed independently up to the response-selection stage (Miller, 1982, 1988) and thus activate response codes at different points in time. If irrelevant spatial stimulus information really activates responses automatically, one may ask what happens to an automatically activated response code during the time the relevant stimulus feature is processed. Hommel (1993) has argued that, since automatic activation is non-intentional by definition, it should decay over time. If so, the size of the Simon effect should depend on the temporal relationship between the processing of the relevant stimulus feature and of the spatial position. Assume, for instance, we would somehow vary the duration of stimulus identification. With fast identification, response selection would occur early in time. Accordingly, the automatically activated response is still highly activated, this leading to a high degree of facilitation or interference, depending on the correspondence condition. However, with slow identification response selection is delayed, so that the automatically activated code should have decayed to a certain degree. Accordingly, a lesser degree of facilitation or interference is expected, that is, an underadditive interaction of S–R correspondence and the factor responsible for the effect on identification.

Fig. 2a shows a typical outcome of a decay experiment (Hommel, 1993, Exp. 3). Subjects responded to the black letters I or T that appeared randomly to the left or right of fixation. The whole stimulus field was white or was overlaid by a pattern of medium or high complexity. There was a main effect of signal quality and a main effect of S–R correspondence. That is, stimulus identification was hampered by the more complex patterns, and responses were faster when the stimulus spatially corresponded to the correct response key – a result that is not very surprising. More importantly, however, there was an underadditive interaction of signal quality and correspondence: The Simon effect disappears and is even reversed

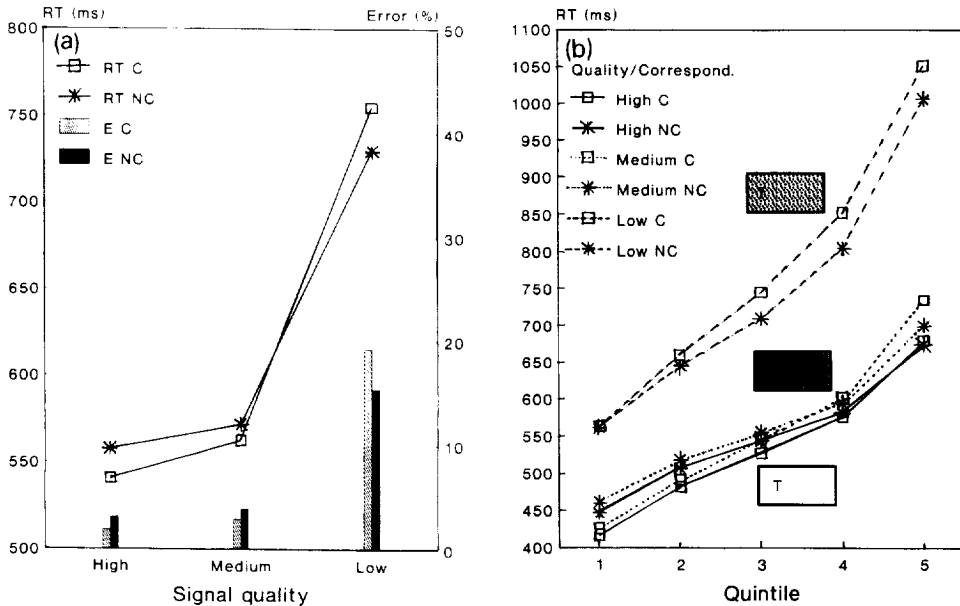


Fig. 2. Panel a shows mean reaction times (RTs; in ms) and error rates (E; in percent) as a function of signal quality and spatial stimulus-response correspondence (C) or noncorrespondence (NC). Panel b shows the same data Vincentized: For each condition, means were computed for the 1st to 5th quintile of the rank-ordered reaction times of each subject. The figure depicts the overall quintiles obtained by averaging over subjects.

with the most complex pattern. Therefore, delaying stimulus identification decreases the effect of correspondence, exactly as the decay hypothesis predicts.

Indications for decay can also be found in reaction time distribution analyses using the Vincentization method of Ratcliff (1979): Fig. 2b shows that fast responses, represented by the first quintiles, uniformly produce a larger correspondence effect than slow responses under all pattern conditions. Similar findings have also been reported by Grice et al. (1984) and by De Jong et al. (1994).

In later studies, the relative speed of the critical stimulus feature was manipulated by varying contrast and retinal eccentricity (Hommel, 1993), stimulus-background discriminability (Hommel, 1994a), stimulus-stimulus similarity (Hommel, 1994b), and memory set size (Hommel, 1995c). The outcome was always the same: The correspondence effect declined with increasing delay of processing of the relevant stimulus feature.

In further experiments, the temporal relationship between the relevant stimulus feature and the positional cue was varied not by delaying the relevant feature but by preexposing the irrelevant one (Hommel, 1993, 1994b). The stimulus letter was either fully presented at once, like in the standard case, or it appeared gradually on the screen, so that position information was available 196 ms before identity

information. As predicted by the decay hypothesis, the correspondence effect decreased with preexposition.

In summary, there is evidence that, first, the relevant stimulus feature and the irrelevant spatial stimulus information are processed independently and, presumably, in parallel; second, the spatial stimulus information activates corresponding responses and, third, that this activation decays over time. Admittedly, the evidence for automatic activation and decay of response code is somewhat indirect; insofar our interpretation critically depends on accepting the proposed decay logic. Fortunately, however, there is converging evidence from studies using more direct means to observe response activation, and this will be reviewed in the following.

3. Psychophysiological evidence

In these experiments, the influence of spatial location on response processes was tracked with the help of the Lateralized Readiness Potential (LRP) that is assumed to be an index of partial response activation (cf. Coles, 1989). The LRP was used to study both the time course and the automaticity of processes underlying the partial activation of compatible responses. In the standard compatibility paradigm, automatic response activation processes and controlled translation processes are triggered at the same point in time (when the imperative stimulus is delivered). De Jong et al. (1994) have recently reported LRP modulations indicating an initial activation of incorrect responses in incompatible trials. However, the fact that automatic and controlled response activation processes operate largely in parallel in usual S–R compatibility experiments, makes it rather difficult to monitor continuously the time course of automatic response activation processes with the help of LRP. Therefore, in the following experiments, automatic and controlled processes were separated in time by eliciting a response activation process *before* the arrival of a target stimulus upon which a response had to be selected. This was done by employing a paradigm where lateralized imperative stimuli were preceded by a precue.

An arrow that pointed either to the left or right was presented for 200 ms at the center of a computer screen. This precue indicated with 75% validity the likely position of the imperative stimulus that followed the cue after an interval of 700 ms. Two letters (M and W) served as imperative stimuli. They were presented for 100 ms on the left or right side of the screen, requiring either a left-hand or a right-hand response. The response hand was determined either by the identity of the letter (with M indicating a left-hand and W a right-hand response) or by letter position (with left and right letters requiring a left-hand or right-hand response, irrespective of their identity). The LRP was computed on the basis of the EEG recorded in the cue–target interval.

Why should one expect to find evidence for response activation processes in the cue–target interval at all? Both targets and responses as well as the cue stimuli can be characterized in spatial terms, since the cues pointed either to the left or right. If irrelevant feature overlap in the spatial domain results in automatic response

activation (cf. Kornblum et al., 1990), one may expect to find LRP evidence for the activation of the response indicated by the arrow direction in the cue–target interval independently of whether the arrow is informative with respect to the nature of the upcoming response. Thus, a “pure” automatic response activation process may be visible in the LRP in the absence of any controlled response selection. While the former process is assumed to be independent of specific S–R mapping rules created by specific instructions, the latter, controlled translation process indeed selects the correct response on the basis of such rules. When the precue is informative with respect to the upcoming response, this controlled process may therefore also be partially activated in the cue–target interval.

In the first experiment, the precue was informative with respect to the response connected to the upcoming imperative stimulus. Here, all stimuli on the left side required a left-hand response, and all stimuli on the right a right-hand response. Since the arrow indicated the position of the target stimuli with 75% validity, it was likely that a response was to be given at the side signalled by the precue. As almost expected, the LRP revealed a systematic tendency to activate the response indicated by the direction of the arrow precue (Fig. 3).

This response activation consisted of two phases, separated by an interval in which the LRP waveform returned back to baseline. However, the cue was informative with respect to the upcoming reaction and could thus have elicited a response activation controlled by specific expectations. Therefore, these results cannot yet be taken as strong evidence for the existence of an involuntary, or automatic response activation triggered by the cue. Therefore, another experiment was conducted where subjects had a strong incentive not to prepare the response compatible to the arrow direction. To achieve this, the response instructions from the first experiment were simply reversed. Left-side letters were connected to right-hand responses, and vice versa, resulting in a probability of 75% that a response contralateral to the arrow directed had to be executed. As can be seen in Fig. 3b, the first LRP modulation phase was very similar to the effects observed in the first experiment. Although the response compatible to the arrow direction was likely to be incorrect, the LRP showed that this response was initially primed. In the later phase of the cue–target interval, however, a very different picture from the one obtained in the first experiment emerged: A reversal of the initially activated response tendencies takes place around the time when the imperative stimulus is presented. It thus seems that specific response probabilities may influence the second, but not the first lateralization phase.

Analogous results have been obtained in a number of additional experiments, where cue informativeness, response probabilities, and cue–target SOA were varied (cf. Eimer, 1995). In all experiments, the LRP revealed the biphasic pattern shown in Fig. 3a and Fig. 3b, with the first phase being remarkably stable during these manipulations. From these results, it may be concluded that evidence for an automatic response activation following the presentation of a spatially directed cue can indeed be found in the LRP: The first lateralization phase, which starts 200 ms after cue onset and remains to be present for about 300 ms, seems to reflect such a process since it is not influenced by objective cue–response contingencies. In

contrast, the second lateralization phase seems to be partially dependent upon specific cue–response contingencies. The fact that the first lateralization phase returns to baseline after about 300 ms may be interpreted as electrophysiological evidence for the decay of automatic response activation that has already been demonstrated by the reaction time studies described before. Alternatively, this effect may be seen as reflecting active response inhibition processes that were activated because the precue was not a very reliable predictor of the upcoming response.

Before interpreting these effects in this way, an alternative interpretation has to be ruled out. In the previous experiments, the cue was always informative with respect to the location of the next target. This should have caused a movement of spatial attention to the indicated position. It is possible that the LRP modulations observed before do not reflect partial response activation processes, but rather the movement of spatial attention. In fact, the assumption that lateralized negativities obtained in trial-by-trial cueing experiments between 200 and 500 ms after cue onset reflect visual-spatial orienting has already been put forward by Harter et al. (1989) and Harter and Anllo-Vento (1991). To rule out this hypothesis, it has to be shown either that (a) the early LRP modulations are absent under conditions where attentional movements are elicited, or that (b) these effects can be obtained under conditions where no attentional movement takes place. Two additional experiments were conducted to study these issues.

In the first of these experiments, non-spatial precues were employed. A red or blue square was presented at the center of the screen. The color of these cues was informative with respect to the position of the upcoming imperative stimulus. Thus, the cues should again elicit an attentional movement towards the probable target location. However, unlike the arrows, these color cues did not possess any spatial characteristics, and should therefore not elicit an automatic response activation process. If the early LRP modulations reported above are due to an activation of spatially compatible responses, they should be absent in this situation. If they owe to attentional orienting, they should be present. In addition, the cue color was informative with respect to the upcoming response, which may be reflected in the second lateralization phase. As can be seen in Fig. 3c, the results of this experiment were straightforward: No LRP modulation was present before 600 ms after cue onset. The initial lateralization phase was completely missing, while the second phase (which is assumed to be sensitive to objective cue–response contingencies) was clearly present. This is strong evidence for the assumption that the early LRP modulation is due to selective motor preparation, and not to attentional orienting.

In the second experiment, arrows were again used as cues. However, in contrast to the previous experiments, all imperative stimuli were presented at fixation, and not on the left or right side of the screen. The arrow direction was informative with respect to the upcoming response. As there are no lateralized targets, no lateral attentional movements should be elicited in the cue–target interval. However, if the LRP effects observed before owe to automatic response activation, an early lateralization should again be visible in the LRP in response to the arrow cue. The

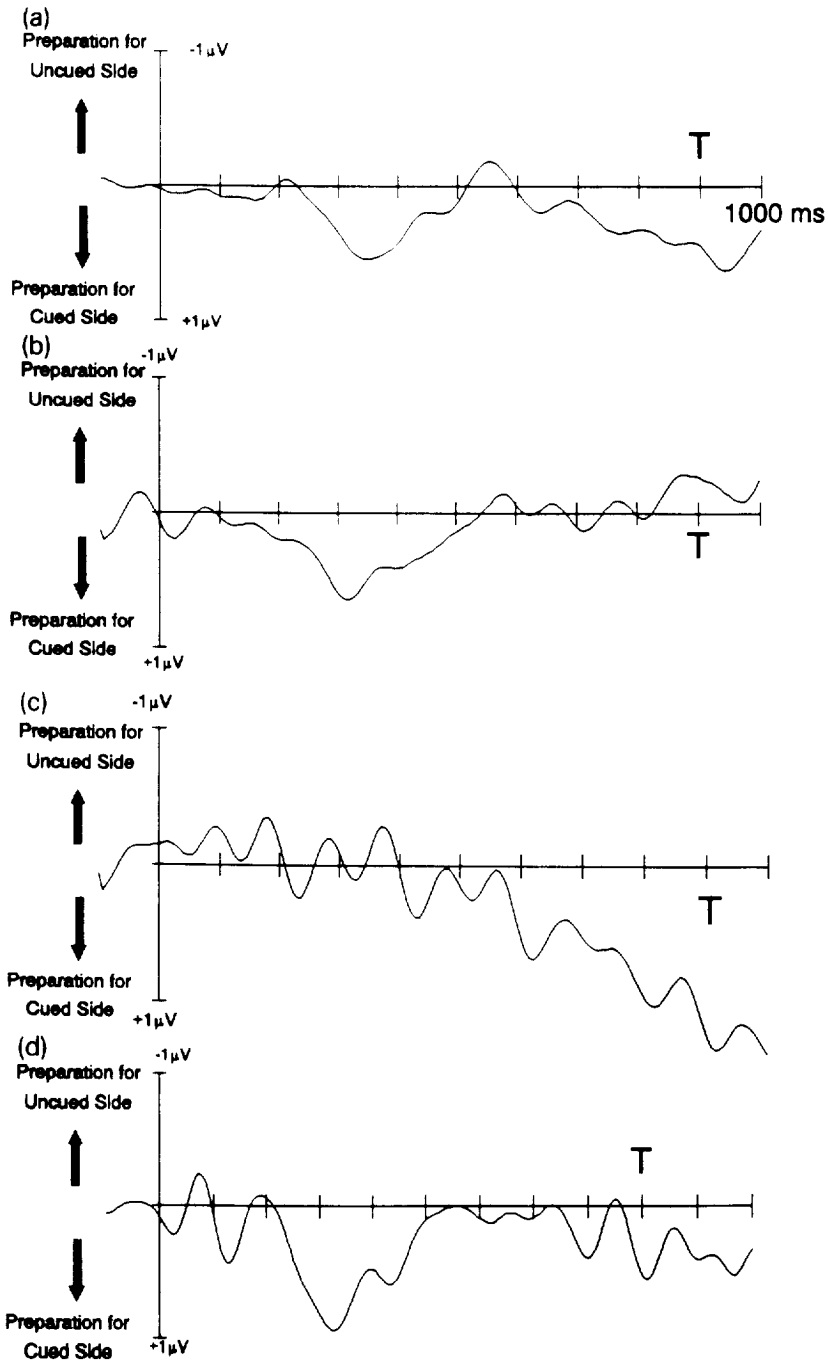


Fig. 3. Lateralized readiness potentials (LRPs) recorded in the interval between cue onset and target onset (T). Downward-going deflections indicate preparation of the response side indicated by the cue. (a) Exp. 1, (b) Exp. 2, (c) Exp. 3, (d) Exp. 4.

results are presented in Fig. 3d: An early LRP modulation was again clearly present. As no attentional movements should have been elicited in this situation, the assumption that the early LRP effect is attentional in nature has thus been ruled out.

In summary, these experiments brought electrophysiological evidence for the existence of a partial response activation process elicited in a cue–target paradigm by cues that possess spatial features overlapping with the response. The LRP revealed an early lateralization between 200 and 500 ms following cue onset. This lateralization was not influenced by objective cue–response contingencies and was absent when the cue lacked the relevant spatial properties. Following this first modulation, the LRP returned back to baseline, presumably reflecting the decay of an automatically activated response tendency. A second response activation phase could then be observed around 200 ms before target onset that was partially controlled by objective cue–response contingencies. In conclusion, the present experiments provided evidence for the existence of automatic response activation processes that are sensitive to spatial stimulus features and are presumably independent of processes that determine target identity and select the correct response.

4. Conclusions

What, then, can be inferred from these findings? First, it seems that a major revision of the theoretical role of (controlled) S–R translation is necessary. We must conclude that the translation process does not protect responses or response codes from being activated. Instead, translation is only one of at least two routes from stimulus to response; automatic activation due to similarity or overlap between stimulus and response features is another one. Of course, neither the two-route assumption nor the notion that S–R translation may be bypassed is really new (see the dual-route conceptions of Van Duren and Sanders, 1988; Los, 1994; and the direct response activation hypotheses of Frith and Done, 1986; Greenwald, 1970; and Sanders, 1967). However, our approach (and that of De Jong et al., 1994; or Kornblum et al., 1990) goes beyond previous approaches in assuming that both routes can be used (a) in parallel, (b) by different codes of the same stimulus.

Second, the demonstration of automatic response activation questions the view that stimulus and response domains are as strictly separated as the translation metaphor implies. Instead, codes from both domains interact in a direct way rather than being mediated by the S–R translation stage. As this suggests some kind of commensurability between codes, we regard it as support for our basic assumption of a common coding system, where both stimulus and response are represented by cognitive codes of the same format and of comparable contents.

A further implication of our findings is that there is more going on in the information processing system than a single stream of information from receptor stimulation to muscle contraction. On the contrary, our results strongly suggest

that preliminary results from stages concerned with stimulus analysis can be transmitted to stages concerned with the preparation and execution of responses, although other stimulus features are still being analyzed. For example, spatial information seems to be processed independently from identity information and seems to reach the stages concerned with response preparation and execution long before the analysis of the relevant identity information is completed.

Even though there is no obligatory discrete processing of the stimulus as a whole this does not rule out the possibility that each stimulus feature, such as position or identity, is processed in a discrete way – like in Miller's Asynchronous Discrete Coding model (Miller, 1982, 1988). Although graded reaction time effects or continuous LRP functions seem to suggest continuous processing, we must not forget that they always represent averages over many trials, implying that we cannot be sure to which extent the smoothness of the functions reflect continuous growth of activation vs. continuous increase of likelihood of all-or-none activation.

With all these reservations in mind, we still think that the notion of fully discrete transmission of information between non-overlapping stages is not supported by the evidence provided. We feel that the time has come that the asynchronous (or even continuous) processing view should now take the role of the standard model of human information processing. As far as this role is concerned, the fully-discrete processing view has done a marvelous job over the last two decades: it has challenged a very stimulating body of research and exciting new insights into the mechanisms underlying human information processing. We have now reached a point where this research and these insights have led to the conclusion that a somewhat more continuous-processing view is both biologically more plausible and heuristically more fruitful than the fully-discrete processing view. Therefore, it should now take over the role of the null hypothesis for further research.

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