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Stimulus–Response Compatibility and the Simon Effect: Toward an Empirical Clarification

Bernhard Hommel
Max Planck Institute for Psychological Research

Perceptual accounts attribute the Simon effect to the correlation between relevant stimulus feature and response location (e.g., T. Hasbroucq & Y. Guiard, 1991). This account is questioned, and it is demonstrated that a Simon effect can be obtained without a stimulus–response correlation (Experiment 1). Experiments 2 and 3 replicated this finding and showed that the relative size of stimuli and response labels and temporal overlap of warning signal and stimulus cannot account for why the effect was absent in Hasbroucq and Guiard's study. However, no Simon effect occurred in a close replication of Hasbroucq and Guiard's original experiment (Experiment 4). Participants' reports suggested that this was due to a special stimulus-coding strategy, and in fact, the effect reappeared with a slightly modified stimulus display (Experiment 5). These results provide strong evidence against a perceptual approach to the Simon effect and support response-related views instead.

The spatial relationship between stimuli and responses is known to be one of the most influential factors in human performance. This influence has often been demonstrated in both applied work and experimental tasks (for reviews, see Loveless, 1962; Proctor & Reeve, 1990). For example, when left stimuli are responded to by pressing a left response key and right stimuli are responded to by pressing a right response key, performance is better (in terms of reaction time and error rates) than when left stimuli are paired with right responses and vice versa. Such phenomena of spatial stimulus–response (S-R) compatibility occur even when the stimulus position is completely irrelevant for the task. For example, if the verbal commands "left" and "right" are presented randomly to the left and the right of the participant, responses are faster when their location corresponds with speaker location (Simon & Rudell, 1967). This impact of compatibility between task-irrelevant stimulus location and response location has come to be known as the *Simon effect.*

In most approaches, the Simon effect has been associated with response selection. Simon (1969) speculated about an automatic tendency to respond toward stimulus location. In later years, he postulated a stimulus-induced bias in the search through response buffers (Simon, Acosta, Mewaldt, & Speidel, 1976). Wallace (1971, 1972) put forth the idea that automatically formed codes of stimulus location may facilitate the activation of similar spatial response codes. Kornblum, Hasbroucq, and Osman (1990), Prinz (1990), and Proctor, Reeve, and Van Zandt (1992) presented more general accounts of compatibility phenomena that are essentially compatible with the claims of Wallace. Even in approaches stressing the possible role of stimulus-related processes in the Simon effect (Stoffer, 1991; Umiltà & Nicoletti, 1992), the effect proper is located at a response-selection stage. However, the traditional view has been challenged only recently by Stoffels, Van der Molen, and Keuss (1989) as well as by Hasbroucq and Guiard (1991; Guiard, Hasbroucq, & Possamai, 1994), who attributed the Simon effect to problems with stimulus identification.

Stoffels et al. (1989) came to their conclusion by using the additive factor method sensu Sternberg (1969): In investigating the effects of irrelevant spatial cues on performance, they found additive effects of cue location and the number of response alternatives. As they related the number effect to response location and excluded influences of the location effect on later stages, it must be located at a preceding stage, hence, stimulus identification.

Hasbroucq and Guiard (1991) proposed a stimulus congruity account. They pointed out that the meaning of the verbal command "left" is congruous with a left command location but not with a right command location. They assumed that two codes are formed at stimulus onset, one referring to the meaning of the stimulus and one to its current location. When both are congruous, performance is better. Although this is an obvious possibility in the case of location-related meanings, other cases of Simon effects with, for example, form stimuli (e.g., Wallace, 1971) are less easy to understand. Suppose that circles and squares are responded to with a left and a right key, respectively. In which way does the meaning of a circle correspond or not correspond to a left or a right position? To account for that, Hasbroucq and Guiard assumed that knowledge about the task-relevant S-R mapping becomes part of the stimulus representation. Because a left response is assigned to a

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Correspondence concerning this article should be addressed to Bernhard Hommel, Max Planck Institute for Psychological Research, Leopoldstrasse 24, D-80802 München, Germany. Electronic mail may be sent via Internet to hommel@mpipf-muenchen.mpg.de.

circle, the circle in this task acquires the meaning *left*. When the circle is then presented on the right side, the meaning code and the location code are incongruous, resulting in weaker performance. To support their ideas, Hasbroucq and Guiard showed that the Simon effect disappears when spatial aspects of the S-R mapping and, thus, the spatial meaning of the stimuli vary from trial to trial.

For several reasons, the perceptual approach to the Simon effect is a major challenge to traditional response-related approaches. First, unlike the traditional approaches, it denies that irrelevant information is automatically transmitted to the response-selection stage. Second, it implies that the Simon effect should be classified as a variant of the Stroop effect (Stroop, 1935; see MacLeod, 1991, for an overview) rather than as a spatial-compatibility phenomenon. That is, virtually all current accounts of the Simon effect (or aspects of it) would be basically incorrect and theoretically misleading in presupposing a more or less strong affinity between the Simon effect and spatial S-R compatibility effects.

As an acceptance of this perceptual approach would have far-reaching implications for compatibility research, a thorough examination of its theoretical and empirical basis is justifiable. In this article, I first present an evaluation of the perceptual account, arguing that it lacks convincing empirical support and theoretical stringency. Then, I report results from five experiments providing strong evidence against this approach. Accordingly, my conclusion is that the perceptual approach to the Simon effect is not a convincing alternative to response-related theories.

Evaluation of the Perceptual Approach

Stoffels et al.'s (1989) perceptual explanation of stimulus location effects was motivated by an interpretation of their results according to the additive factor method. In particular, they rejected the idea that effects of irrelevant spatial cues might be related to response selection on the ground that the location effect does not vary with the number of response alternatives.

There are, however, a variety of possible objections to such a conclusion. First, it rests on the acceptance of a null effect. It may well be that varying the number of response alternatives within a larger range would produce the missing interaction (see Hommel, 1993b). Second, it disregards many possible alternative interpretations that would be equally compatible with the results. As some of these alternatives were discussed by Stoffels et al. (1989) themselves (but were rejected for debatable reasons), there is no need to repeat them here. Third, effects of irrelevant spatial information are known to depend on response uncertainty (Callan, Klisz, & Parsons, 1974). It is hard to see how a perceptual conflict should depend on that. Fourth, Stoffels et al. (as well as Hasbroucq & Guiard, 1991) claimed the location effect to be a kind of Stroop effect. If this were the case, one would expect an interaction of Stroop effect and location effect, but this has not been obtained (Kornblum, 1994; Simon & Berbaum, 1990). Fifth, an additive factor interpretation in favor of an identification-related view makes sense only if location effects would exclusively interact with identification-related factors but not with factors that presumably affect earlier or later stages. This has been contradicted by several findings, namely interactions of stimulus location with stimulus eccentricity (Hommel, 1993b; Simon, Craft, & Small, 1971), distractor intensity (Simon, Craft, & Small, 1970), interstimulus similarity (Hommel, 1994b), stimulus–context similarity (Hommel, 1994a), signal quality and signal contrast (Hommel, 1993b), memory set size (Hommel, in press), and with the introduction of a secondary task (McCann & Johnston, 1992). That is, the interpretation of the presence or the absence of statistical interactions does not seem to be a reliable means of explaining effects of irrelevant spatial information. So, all in all, the conclusions of Stoffels et al. lack empirical support.

The most relevant evidence in favor of the perceptual approach put forth by Hasbroucq and Guiard (1991) was obtained in their second experiment, in which a red and a green stimulus were assigned to a red- and a green-labeled response key, respectively. However, in each trial, the response keys' color labels could change randomly, so that each key color alternated between the left and the right side. As a result of such a complete decorrelation of response location and stimulus color, the Simon effect disappeared; that is, the spatial relationship between stimulus and response had no significant effect on response speed. Hasbroucq and Guiard concluded that this was consistent with their own perceptual view but inconsistent with the traditional response-selection approach.

At second glance, however, this conclusion turns out to be stronger than the empirical base supporting it. Interestingly, Simon et al. (1976) demonstrated that the Simon effect can occur under conditions essentially identical to those of Hasbroucq and Guiard (1991), that is, under complete decorrelation of response location and the relevant stimulus attribute. Although this result is inconsistent with their findings and is damaging to their theoretical considerations, Hasbroucq and Guiard did not comment on it. The demonstration of a solid Simon effect in the Simon et al. study was especially problematic for Hasbroucq and Guiard: Their own empirical evidence rested on a single null effect that still reached an error probability of .17 in an analysis of 8 participants who had all worked through a series of four different tasks! So, there is reason to raise doubts in the empirical support of Hasbroucq and Guiard's perceptual approach to the Simon effect.

Moreover, the perceptual approach lacks theoretical clarity and parsimony (cf. Barber, O'Leary, & Simon, 1994; O'Leary, Barber, & Simon, 1994). This becomes obvious when one considers how responses are selected. Note that the perceptual approach proposes an automatic activation of the response-related meaning of the stimulus. As the automatically activated meaning is assumed to be identical with the knowledge about a certain S-R assignment, the question of why response-selection processes are there is raised. For example, should one assume that there are cases when the participant knows that the presented stimulus requires Response X but has no idea which response to perform? It seems more parsimonious to suppose that cognitive representations of action features, that is, meanings in the sense of Hasbroucq and Guiard (1991), are involved in response selection, as already claimed by Lotze (1852), James (1890), Greenwald (1970), and others. If so, activation of meaning would be tantamount to the activation of a response code, thus suggesting a response-related explanation of location effects. To be sure, this description does not logically exclude any participation of meaning or response codes in stimulus identification but is clearly inconsistent with the perceptual approach under discussion.

Experiment 1

So far, I have presented arguments showing that a perceptual account of the Simon effect and related phenomena is theoretically underspecified and has little empirical support. Experiment 1 was designed to provide empirical evidence for (or against) this criticism. The general idea was to present the irrelevant spatial stimulus information after stimulus identification was completed but still before the response was actually emitted. According to the perceptual account, this should make the Simon effect disappear, because location information has no chance to impair identification-related processes. In contrast, traditional coding approaches predict a Simon effect, because spatial information is assumed to automatically affect response selection. As long as the response is not performed, either its own code or that of another competing response can be (additionally) activated, thus leading to response competition, hence, a Simon effect.

In the present task, the participants received completely valid information about the response in each trial. They had about 1 s to register and identify the centrally presented response cue, which should be enough time to complete any stimulus-identification processes. However, there was a second stimulus, appearing randomly to the left or the right side. This was a green Go or a red No-go signal, indicating whether the precued response should be performed or suppressed. Note that the colors of these signals were not correlated with response locations, so they should not have acquired any location-related "meanings" in the sense of Hasbroucq and Guiard (1991). Thus, neither of the locations were congruous or incongruous with features of the go and no-go signals, so there should have been no identification problems associated with them. Nevertheless, they did provide spatial information. As identification of the response cue should have been completed at the go signal onset and no identification problems related to go or no-go signals were expected, any effect of go signal location would indicate a problem with response selection (assuming that "later" effects can be excluded). That is, whereas the perceptual approach predicts the absence of any Simon-type effect associated with the go signal, traditional response-related approaches predict its presence.

Method

Participants. Ten adult volunteers served as paid participants. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus and stimuli. Stimulus presentation and data collection were controlled by a Hewlett Packard Vectra QS20 computer, interfaced to an Eizo Flexscan 9070S or 9080i monitor. Viewing distance was approximately 60 cm. Participants responded by pressing the left-hand or the right-hand shift key of the computer keyboard with the corresponding index finger. They saw a gray (6 cd/m^2) rectangular frame of 1.2° × 1.2° at the center of a black screen. Stimuli were three white arrows (42 cd/m^2) pointing to the left or the right side and always appearing at the same central location inside the frame. Go and no-go signals were 1.0° × 1.8° patches of green (27 cd/m^2) and red (10 cd/m^2) color, appearing 1.2° to the left and the right (center to center) of the frame.

Procedure. The experiment took place in a dimly lit room. The sequence of events in each trial was as follows: After an intertrial interval of 2,000 ms, the stimulus appeared for 500 ms. A randomly determined interval of 400–600 ms followed, before the go or the no-go signal appeared for 100 ms. The program waited until a response was given, but not longer than 1,000 ms. Responses with the wrong key were counted as errors, and those with latencies exceeding 1,000 ms were considered missing. In both cases, the trial was recorded and then repeated at some random position in the remainder of the block. The participants could delay the next trial by keeping the key depressed if they felt confused or inattentive.

The experiment was run in single sessions lasting about 20 min, with a postexperimental interview concerning strategies or problems with the task. Participants worked through 2 warm-up blocks and 50 experimental blocks. Each block was composed of eight randomly mixed trials, whose type resulted from the factorial combination of stimulus type or response location (left or right), trial type (go or no-go), and location of go or no-go signal (left or right).

Results

False alarms, that is, incorrect responses to no-go signals (<2%) were as rare as missing go trials (<1%). From the remaining data, mean reaction times (RTs) of valid trials and proportions of errors (PEs) were calculated for each combination of go signal location and response location (see Table 1). These data were subjected to 2 × 2 analyses of variance (ANOVAs) for repeated measures.

For RT data, two effects were significant. First, the main effect of go signal location, $F(1, 9) = 8.99$, $p < .05$,

Table 1
Mean Reaction Times (RTs; in Milliseconds) and Proportions of Errors (PEs) in Experiment 1 as a Function of Go Signal Location and Response Location

	Location of go signal			
	Left		Right	
Response location	RT	PE	RT	PE
Left	392	1.0	425	3.7
Right	441	6.4	389	1.2

indicated that responses were faster to right than to left go signals (407 ms vs. 417 ms, respectively). Second, there was a significant interaction of go signal location and response location, $F(1, 9) = 5.64$, $p < .05$, showing that left responses were faster to left than to right signals, whereas right responses were faster to right than to left signals. For PEs, only the interaction term was significant, $F(1, 9) = 19.75$, $p < .005$, indicating less errors with spatial correspondence of go signal and response than with noncorrespondence. The interview did not reveal any special, interindividually consistent strategies.

Discussion

The purpose of this experiment was to compare predictions from a perceptual approach to the effect of irrelevant spatial information on performance with predictions from the more traditional response-related view. The first approach predicts that no effect should occur, whereas the latter predicts a normal Simon-type effect. The results are clear-cut in showing a Simon effect related to the location of the go signal in both RT and error data. The effect size of 43 ms is comparable to results of other studies in which visual color stimuli were used (e.g., Hasbroucq & Guiard, 1991, Experiment 1; Hedge & Marsh, 1975; Hommel, 1993c). These findings are inconsistent with the assumptions of Stoffels et al. (1989) as well as of Hasbroucq and Guiard and provide strong evidence against a perceptual approach.

It should be emphasized that it is not the finding of a Simon effect in a go–no-go task per se that is hard to handle from a perceptual perspective. In fact, the presence of Simon effects in such a task has already been demonstrated by Callan et al. (1974). However, in the Callan et al. study, there was only one possible (left- or right-side) reaction in each experimental block, which had to be emitted in response to one of the two stimulus alternatives but not to the other. In this kind of design, the relevant stimulus feature (i.e., pitch) is perfectly correlated with response side, so that the occurrence of a Simon effect (i.e., faster responding with spatial correspondence of go stimulus and response key) can be easily explained along the lines of Hasbroucq and Guiard's (1991) perceptual approach. In contrast, the present experiment used a go–no-go task in which the go stimulus feature (green color) was in no sense correlated with response side, and it is this decorrelation that stands in the way of a perceptual account of the present results.

Experiment 2

The results of Experiment 1 clearly demonstrate that Simon effects do not depend on the correlation of stimulus feature and response. However, this begs the question of why then Hasbroucq and Guiard (1991) failed to find a significant Simon effect in a task that was similar to that of Simon et al. (1976), who did find a strong effect. The following two experiments were designed to test two hypotheses that deal with possible reasons.

Experiment 2 investigated whether the appearance or the nonappearance of the Simon effect depends on the way participants scan the display. In the Hasbroucq and Guiard (1991) experiment, the participants faced a stimulus display that was much more complex than in a standard Simon task. First, three warning signals went on that stayed on until the response was emitted. Second, the stimulus appeared in a left or a right location, accompanied by two response labels. That is, the participants reacted to a display of six stimuli of three different colors and not to a single stimulus as in a normal Simon experiment. Because the correct response presupposed a comparison of at least two stimuli—the stimulus signal proper and the response label sharing the same color—the order in which these two signals were scanned might have played a role.

Some of the first evidence for the plausibility of a scanning hypothesis came from a study by Schulz (1993), who reported about a failure to replicate the results of Hasbroucq and Guiard (1991). By presenting the stimuli on a computer monitor (Hasbroucq and Guiard used a small box with light-emitting diodes) and by using rather large response labels, Schulz found a substantial Simon effect, although Hasbroucq and Guiard's decorrelation procedure was used. It is plausible to assume that large response labels draw attention to the labels first, whereas the stimulus proper would be scanned only in second place. If one further speculates that response-coding processes responsible for the Simon effect can occur or can be completed only if they precede stimulus processing for a certain time, the appearance of the Simon effect may critically depend on scanning order. Therefore, the effect may occur when, for some reason, the response labels, not the stimulus, are scanned first. If some subtle details of the tasks of Hasbroucq and Guiard (1991) and Simon et al. (1976) would have differed in such a way to induce different scanning orders, the differences between their results would have found a ready explanation.

In Experiment 2, I sought to induce different scanning orders in two different experimental groups by systematically varying the sizes of the stimuli proper and the response labels. The idea was that, according to my interpretation of the Schulz (1993) findings, larger stimuli would be more salient and, thus, scanned earlier than smaller ones. In one group, denoted Sr, the stimulus proper (S) was much larger than the response labels (r; see Figure 1, left panel), whereas for the second group, denoted sR, the response labels (R) were much larger than the stimulus proper (s). The procedure followed Hasbroucq and Guiard's (1991), in that response labels varied randomly from trial to trial. Accordingly, stimulus features and response locations were completely uncorrelated.

If the scanning hypothesis is correct, a Simon effect should occur in Group sR but not in Group Sr. In Group sR, response labels should be scanned first, like (possibly) in the studies of Simon et al. (1976) and Schulz (1993). However, in Group Sr, the stimulus proper should be scanned first, like (possibly) in the Hasbroucq and Guiard (1991) study. If the Simon effect really depended on response labels being scanned some time before the stimulus proper, its preconditions would not be fulfilled in this group. This should lead

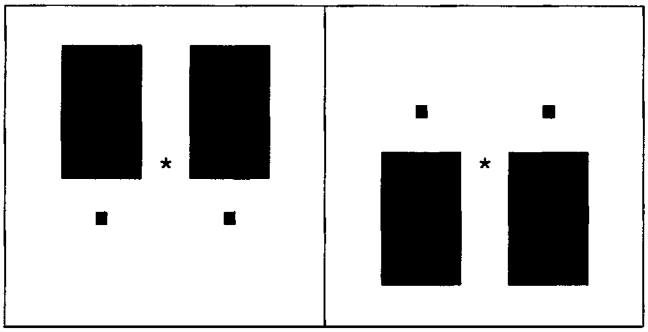

Figure 1. Diagram of the stimulus display in Experiment 2. For Group Sr, the stimuli were large and the response labels were small (left panel), whereas the opposite was true for Group sR (right panel). Note that the fixation asterisk was actually no more visible on stimulus presentation and that only one of the (upper) stimulus rectangles appeared in a trial.

to an elimination of the effect, similar to what Hasbroucq and Guiard reported.

Method

Participants. Thirty-two adult volunteers served as paid participants. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Sixteen participants were assigned randomly to each of the two experimental groups.

Apparatus and stimuli. The same apparatus as in Experiment 1 was used. Figure 1 shows the stimulus displays for both experimental groups. A white asterisk (42 cd/m^2) appearing at the center of the screen served as the fixation point. The stimuli were blue (5 cd/m^2) and green (27 cd/m^2) rectangles of 1.6° × 3.0° (Group Sr) or 0.2° × 0.2° (Group sR), centered 0.6° above the fixation point and 1.2° to the left or the right of it. The response labels were blue and green rectangles of 1.6° × 3.0° (Group sR) or 0.2° × 0.2° (Group Sr), centered 0.6° below the fixation point and 1.2° to the left or the right of it.

Procedure. The sequence of events in each trial was as follows: After an intertrial interval of 2,000 ms, the fixation asterisk appeared for 500 ms, followed by a blank interval of 100 ms. Then, the blue or the green stimulus was presented randomly to the left or the right of fixation. It was always accompanied by the two (blue and green) response labels, whose location was also randomly determined. The three rectangles stayed until a response was given, but not longer than 1,000 ms. The remaining procedure was as in Experiment 1.

The experiment was run in single sessions lasting about 30 min, followed by the postexperimental interview. Participants worked through 3 warm-up blocks and 26 experimental blocks. Each block was composed of eight randomly mixed trials, whose type resulted from the factorial combination of stimulus location (left or right), stimulus type or response location (left or right), and location of response labels (blue label left and green label right or green label left and blue label right).

Results

Missing trials (<0.5%) were excluded from analyses. Mean RTs and PEs per participant, stimulus location, and response location were calculated (see Table 2). ANOVAs were performed with group (Sr or sR) as a between-groups variable and stimulus location as well as response location as within-groups variables.

The RT analysis yielded three significant effects. First, a main effect of stimulus location, $F(1, 30) = 4.32$, $p < .05$, indicated slightly faster responses to left stimuli than to right stimuli (518 ms vs. 523 ms, respectively). Second, a modification of this effect by a Group × Stimulus Location interaction, $F(1, 30) = 11.99$, $p < .005$, showed that the left-side advantage was present and pronounced in Group Sr (520 ms vs. 532 ms) but not in Group sR (516 ms vs. 513 ms). Third, and most important, a highly significant Stimulus Location × Response Location interaction, $F(1, 30) = 37.97$, $p < .001$, indicated that left responses were faster to left than to right stimuli (506 ms vs. 538 ms, respectively), whereas right responses were faster to right than to left stimuli (508 ms vs. 531 ms, respectively). This effect of 28 ms overall was not modified by group ($p > .29$). The PE analysis yielded only a main effect of stimulus location, $F(1, 30) = 9.80$, $p < .005$, produced by higher error rates connected with right than with left stimuli (3.3% vs. 2.3%, respectively). The interview did not reveal any systematic strategies over participants.

Discussion

The purpose of Experiment 2 was to test a scanning hypothesis for explaining the empirical inconsistencies between the findings of Hasbroucq and Guiard (1991) and those of Simon et al. (1976), Schulz (1993), and the present Experiment 1. This hypothesis states that when stimulus and response labels are presented simultaneously, the order in which they are processed may play a role in whether a Simon effect occurs. In Group Sr, large stimuli should have induced a tendency to scan the stimulus proper first, which again should have prevented a Simon effect. In Group sR, however, large response labels should have attracted atten-

Table 2
Mean Reaction Times (RTs; in Milliseconds) and Proportions of Errors (PEs) in Experiment 2 as a Function of Group, Stimulus Location, and Response Location

	Stimulus location			
	Left		Right	
Response location	RT	PE	RT	PE
	Group Sr			
Left	509	3.6	544	3.6
Right	532	2.3	521	4.7
	Group sR			
Left	502	1.5	532	2.7
Right	531	2.0	495	2.2

Note. For Group Sr, the stimulus proper (S) was much larger than the response labels (r). For Group sR, the response labels (R) were much larger than the stimulus proper (s).

tion first, resulting in a Simon effect. Nevertheless, the results very clearly demonstrate that the scanning hypothesis can be ruled out.

First, there was no indication for any impact of the stimulus size manipulation on the size of the Simon effect. Even though the interaction between group and stimulus location shows that the size variable was not completely ineffective, neither the RT data nor the error data support the scanning hypothesis. To the extent that the size manipulation did induce different scanning orders, one can conclude that the Simon effect does not depend on this variable.

Second, pronounced Simon effects occurred in both groups, although stimulus features and response locations were completely uncorrelated! This is consistent with and adds to the evidence presented by Simon et al. (1976) and Schulz (1993) and demonstrated in Experiment 1, but it stands in clear contrast to the findings and the theoretical ideas of Hasbroucq and Guiard (1991).

Experiment 3

A further factor preventing a Simon effect in the study by Hasbroucq and Guiard (1991) may have been the temporal characteristic of the warning signal they used. As described above, each stimulus presentation, comprising both the stimulus proper and the two response labels, was preceded by a row of three warning lights. These lights stayed on until a response occurred, so that stimuli and warning lights overlapped in time. Because no such overlap was present in the studies that did find a Simon effect with uncorrelated stimulus and response features, Hasbroucq and Guiard's missing effect may be related to that. Consequently, the aim of Experiment 3 was to examine whether this warning-signal hypothesis holds.

There are several reasons why a temporal overlap may prevent a Simon effect. One is that the presence of additional response-irrelevant stimuli effectively changes the task into a visual search task. This can be expected to delay the identification of the stimulus, which might result in a decrease or even the disappearance of the Simon effect (Hommel, 1994a). One problem with this argument is that it also applies to Hasbroucq and Guiard's (1991) Experiment 1, which, even so, gave rise to a pronounced Simon effect. However, the response labels were constant in that experiment; therefore, the participants could have focused their attention on the possible stimulus locations, probably ignoring the warning signals. This was not possible in Hasbroucq and Guiard's Experiment 2, because both the stimulus (in the uppermost row of the display) and the response labels (in the lowermost row of the display) varied randomly, with the warning-signal row falling in between.

Another reason why the temporal overlap of warning signals and stimuli may prevent a Simon effect has been put forth by Proctor and Lu (1994). They assumed that such an overlap delays or even prevents the shifting of attention from the former to the latter. That is, the continuing presence of a fixation point may, in a sense, lock the attentional focus, so that the upcoming stimulus is analyzed without moving attention to its location. Under the further assertion that the Simon effect critically depends on attentional shifts (see Stoffer, 1991; Umiltà & Nicoletti, 1992), the Simon effect may be prevented by a continuously visible warning signal. It is true that this perspective also has some difficulties. Again, one would like to know why the Simon effect was not prevented in Hasbroucq and Guiard's (1991) Experiment 1, too. Nevertheless, it should be clear that assuming a possibly critical role of a temporal overlap of warning signal and stimulus can be motivated by several theoretical perspectives.

In Experiment 3, I investigated the warning-signal hypothesis by simply varying groupwise whether warning signal and stimulus did or did not overlap in time. In one group, called the steady group, the warning signal was visible until the response was emitted. As this procedure was similar to Hasbroucq and Guiard's (1991), no Simon effect was expected. In the other group, called the transient group, the warning signal went off 200 ms before stimulus onset. As this procedure was similar to that of Simon et al. (1976), Schulz (1993), and the present Experiment 2, a Simon effect was expected to occur.

Method

Participants. Thirty-two adult volunteers served as paid participants. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Sixteen participants were assigned randomly to each of the two experimental groups.

Apparatus and stimuli. The same apparatus as in Experiment 1 was used. Figure 2 shows the stimulus display. A row of three white asterisks (42 cd/m^2) appearing at the center of the screen served as warning signals. The stimuli, blue (5 cd/m^2) and green (27 cd/m^2) rectangles of 0.3° × 0.6°, appeared 0.6° above the leftmost or the rightmost warning asterisk. The response labels, blue and green rectangles of the same size as the stimuli, appeared 0.6° below the leftmost and the rightmost warning asterisk.

Procedure. Each trial began with an intertrial interval of 2,000 ms, followed by presentation of the warning signal. In the transient

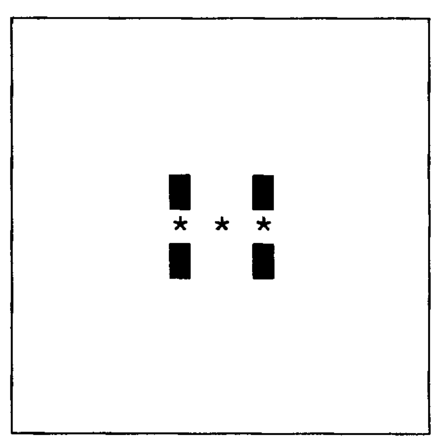

Figure 2. Diagram of the stimulus display in Experiment 3. Note that the row of asterisks actually disappeared before stimulus presentation in the transient group and that only one of the (upper) stimulus rectangles appeared in a trial.

group, the asterisk row disappeared after 500 ms, followed by a blank interval of 200 ms. Then, the blue or the green stimulus was presented randomly to the left or the right of fixation, accompanied by the two (blue and green) response labels. The three rectangles stayed until a response was given, but not longer than 1,000 ms. In the steady group, the procedure was identical except that the row of asterisks was not deleted after 500 ms but remained visible until the response was given. In all other respects, the procedure and the design were the same as in Experiment 2.

Results

Missing trials (<0.5%) were excluded from analyses, and the remaining data were treated analogously to Experiment 2. Mean RTs and PEs are given in Table 3.

There were only two significant effects, demonstrating the presence of Simon effects (i.e., Stimulus Location × Response Location interactions) in both RTs, $F(1, 30) = 57.79$, $p < .001$, and PEs, $F(1, 30) = 6.11$, $p < .05$. Left responses were faster and less often incorrect to left than to right stimuli (470 ms vs. 508 ms and 1.4% vs. 2.5%, respectively), whereas right responses were faster and less often incorrect to right than to left stimuli (468 ms vs. 503 ms and 1.8% vs. 2.9%, respectively). There was no sign of a modification of this effect by warning signal in the RT ($p > .4$) or the PE data ($p > .5$). Again, the interview did not reveal any systematic strategies over participants.

Discussion

The purpose of Experiment 3 was to examine whether the temporal overlap of warning signal and stimulus might have prevented the Simon effect in Hasbroucq and Guiard's (1991) Experiment 2. In the steady group, there was such an overlap; therefore, no Simon effect should have occurred here, too. In the transient group, the warning signal went off before stimulus onset, so a standard Simon effect was expected. The results, however, were the same as in Experiment 2: On the one hand, large Simon effects occurred in both experimental groups despite a null correlation of stimulus features and response locations. This provides further evidence that it cannot be this decorrelation that made the Simon effect disappear in the Hasbroucq and Guiard study. On the other hand, the size of the Simon effect was unaffected by the warning-signal manipulation. Obviously, it is of no relevance whether there is a temporal overlap between warning signal and stimulus, thus ruling out the warning-signal hypothesis.

Table 3
Mean Reaction Times (RTs; in Milliseconds) and Proportions of Errors (PEs) in Experiment 3 as a Function of the Type of Warning Signal, Stimulus Location, and Response Location

	Stimulus location			
	Left		Right	
Response location	RT	PE	RT	PE
	Warning transient			
Left	468	2.1	508	2.5
Right	503	3.3	464	2.0
	Warning steady			
Left	473	0.6	507	2.5
Right	503	2.5	473	1.7

Experiment 4

The two preceding experiments sought an explanation for why the Simon effect in the Hasbroucq and Guiard (1991) study disappeared. As neither the size manipulation in Experiment 2 nor the warning-signal manipulation in Experiment 3 was successful in reducing or eliminating the Simon effect, I was still in need of a plausible causal factor. To get a grasp of what kind of factor this might be, I decided to run an exact replication of the relevant condition of Hasbroucq and Guiard's experiment (i.e., the color-to-color condition of their Experiment 2). As already pointed out in the evaluation of the perceptual approach, the relevant statistical results of their study were not too impressive, so that all may have been a statistical power problem. Furthermore, the participants were run through four tasks, each with a different kind of task relevance of location and color of stimulus and response label. Therefore, the Simon effect's disappearance may have been due to an intertask transfer effect.

To copy the Hasbroucq and Guiard (1991) experiment as exactly as possible, a box was constructed for stimulus presentation and response measurement identical to that of the original experiment except for some minor deviations in the exact size of the box outline and the location and diameter of the warning lights (see Figure 3). The procedure was also identical to the original procedure, as given in the article (see Hasbroucq and Guiard's color-to-color condition). Thus, if the Simon effect's disappearance were a genuine effect and not a statistical or methodological artifact, it should be replicated with this task.

Method

Participants. Ten adult volunteers served as paid participants. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus and stimuli. The experiment was controlled by an Atari Mega STE computer, interfaced to an apparatus for stimulation and response very similar to that used by Hasbroucq and Guiard (1991). As illustrated in Figure 3, it consisted of a light gray, rectangular (8 cm × 10 cm × 3 cm), aluminum box, equipped with two response keys at its bottom end. The box was handheld, so that response keys were operated with the left and the right thumb. Above the keys, there were three rows of light-emitting diodes (LEDs), each 0.5 cm in diameter. The uppermost row consisted of two bicolor LEDs that served as stimuli by being illuminated red or green. In the middle row, three yellow LEDs served as warning signals. The lowermost row again consisted of two bicolor LEDs, serving as red or green response labels. From a viewing distance of approximately 60 cm, the distance between the two stimulus (or response label) locations was about 3°, and the distance between the stimuli and the response labels was about 2°.

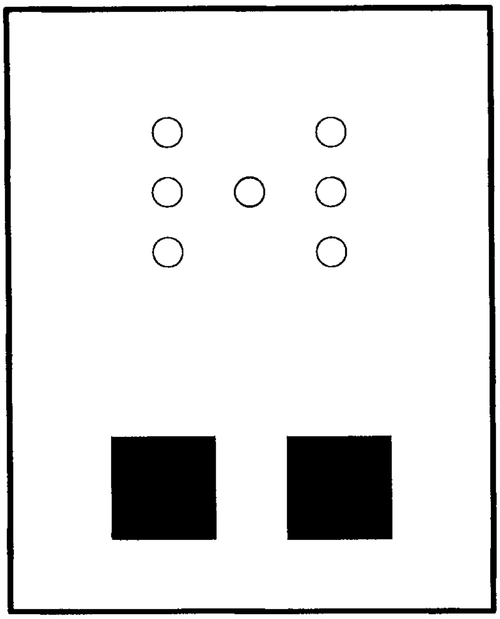

Figure 3. Diagram of the apparatus used in Experiment 4 for stimulus presentation and response measurement. Locations of bicolor stimulus lights, yellow warning signals, and bicolor response label lights are indicated by the uppermost, middle, and lowermost row of circles, respectively. Response key locations are indicated by the solid rectangles at the bottom.

Procedure. The procedure was identical to Hasbroucq and Guiard's (1991, Experiment 2, color-to-color condition). Following an intertrial interval of 4,000 ms, the three warning LEDs went on simultaneously. After 700 ms, one of the two stimulus lights and both response label lights were lit simultaneously. The color and the location of the stimulus light and the response labels varied randomly from trial to trial. The program waited, and the six lights stayed on until the response was given, but not longer than 1,500 ms. Responses with the wrong key were counted as errors, and those with latencies exceeding 1,500 ms were considered missing. Both kinds of errors were fed back by a short beep but, following the Hasbroucq and Guiard procedure, were not replaced. The instruction asked the participant to press the key below the label light that shared its color with the stimulus. It stressed that stimulus location would be randomly determined and emphasized both speed and accuracy.

The experiment was run in single sessions lasting about 25 min, followed by the postexperimental interview. Participants worked through four blocks, each consisting of 4 warm-up trials and 64 experimental trials. Each block was composed of eight replications of each of the eight possible combinations of stimulus location (left or right), stimulus color or response location (left or right), and location of response labels (red label left and green label right or green label left and red label right). As in the Hasbroucq and Guiard (1991) procedure, each trial realized 1 of the 64 possible trial-to-trial transitions.

Results

There were no missing trials, most likely because of the raised upper RT limit in this experiment. The data were treated analogously to Experiment 2. Mean RTs and PEs are given in Table 4.

The only effect revealed by the RT analysis was one of response location, $F(1, 9) = 8.33$, $p < .05$, showing that right responses were faster than left responses (398 ms vs. 413 ms, respectively). The Stimulus Location × Response Location interaction was far from significant ($p > .2$). The same was true for the error analysis ($p > .4$), which also yielded no other significant effect. Practice effects were assessed by RT analyses, with experimental half as a further variable. However, this did not change anything, except that there was a main effect of half, $F(1, 9) = 9.54$, $p < .05$. Most interesting, the (null) effect of S-R correspondence was not modified by practice ($p > .26$).

Discussion

The purpose of Experiment 4 was to replicate as exactly as possible the experiment of Hasbroucq and Guiard (1991, Experiment 2, color-to-color condition) to test whether the disappearance of the Simon effect in their study could have been due to a methodological artifact or a statistical power problem. The results are very clear in rejecting both possibilities. Although every kind of intertask transfer was excluded here, the findings of Hasbroucq and Guiard were fully replicated. That is, there is no indication of a Simon effect, neither in RTs nor in error rates. Thus, although the original results may be interpreted as reflecting a number-of-participants problem, the present results rule out such an interpretation. Obviously, the disappearance of the Simon effect is a real effect. The only problem is that, in view of the findings in Experiments 1–3, it cannot be attributed to the factor favored by the original authors, namely the decorrelation of stimulus feature and response side. So, where does it come from?

One possible explanation was suggested by the participants' answers in the postexperimental interview, which included one question regarding the strategy pursued during the task. Although in most experiments (including the present Experiments 1–3) participants respond very inconsistently to this question, here they all gave more or less the same answer. They stated that they did not scan the stimulus or the response first and then continue with the other, nor did they perceive the configuration of stimulus light, warning light, and response labels as a whole. Instead, they perceived a line made up of the stimulus light and the

Table 4
Mean Reaction Times (RTs; in Milliseconds) and Proportions of Errors (PEs) in Experiment 4 as a Function of Stimulus Location and Response Location

	Stimulus location			
	Left		Right	
Response location	RT	PE	RT	PE
Left	408	3.1	418	5.3
Right	402	3.1	394	3.3

response label as a kind of figure on a colored background. This red or green line always pointed to the correct response key, although it was a straight line in compatible trials and a diagonal line in incompatible trials. Whether the stimulus or the response was located on the left or the right side seemed to be completely irrelevant to the participants, at least as far as their phenomenal experience was concerned.

As these self-reports fit exactly to the data, they may serve as the basis for a tentative perceptual-grouping explanation of the disappearance of the Simon effect in Experiment 4 as well as in the original experiment by Hasbroucq and Guiard (1991). That is, in these experiments, the stimulus display was probably not perceived as consisting of a left or a right stimulus and a left or a right response label, but of a central line pointing to the correct response. As this imaginary line is not located to the left or the right, there can be no spatial S-R correspondence or noncorrespondence, and therefore, no Simon effect can occur.

Experiment 5

The proposed perceptual-grouping hypothesis is completely post hoc and thus calls for independent support, which I intended to obtain in an additional experiment. The general idea was to leave as much detail of the setup of Experiment 4 but still to induce a different way to organize the stimulus field. Figure 4 shows the result of this attempt: After removing the central yellow warning light, the S-R apparatus of Experiment 4 was taped with black foil, so that two vertical bars—surrounding the left and the right column of LEDs, respectively, and the corresponding response key—appeared on a black background. This manipulation was thought to counteract the presumed tendency to perceive noncorresponding S-R combinations as diagonals and to induce instead a partitioning of the visual field into a left and a right figure or gestalt. If so, stimuli and response labels within these figures should be more likely coded as left or right than in Experiment 4; therefore, a substantial Simon effect was expected. In contrast, as critical stimulus features and response locations were again uncorrelated, the perceptual approach to the Simon effect predicts the same result as in Experiment 4, hence, a null effect.

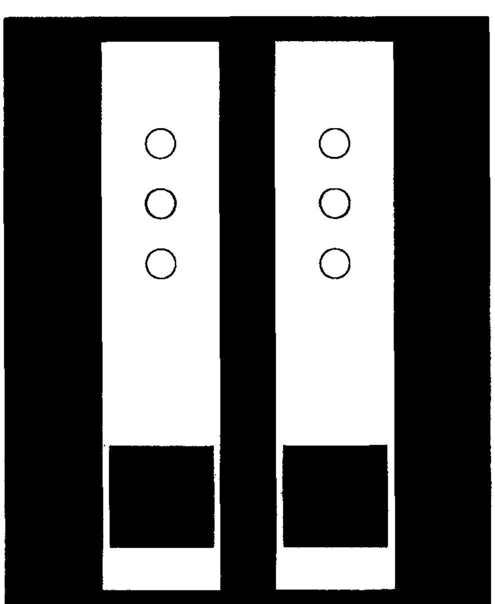

Figure 4. Diagram of the apparatus used in Experiment 5.

Table 5
Mean Reaction Times (RTs; in Milliseconds) and Proportions of Errors (PEs) in Experiment 5 as a Function of Stimulus Location and Response Location

	Stimulus location			
	Left		Right	
Response location	RT	PE	RT	PE
Left	437	1.4	458	2.4
Right	449	3.3	431	0.8

Method

Participants. Twelve adult volunteers served as paid participants. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus, stimuli, and procedure. These were the same as in Experiment 4, except that the S-R apparatus was modified as described and the instruction explicitly mentioned the "left and right bar."

Results

Missing trials (<0.1%) were excluded, and the remaining data were treated as in Experiment 4. Mean RTs and PEs are given in Table 5.

The RT analysis yielded a significant interaction of stimulus location and response location, $F(1, 11) = 6.19$, $p < .05$, showing that left responses were faster to left than to right stimuli, whereas the opposite was true for right responses. Likewise, the PE analysis confirmed that left responses produced less errors with left than with right stimuli, whereas right responses were more often correct to right than to left stimuli, $F(1, 11) = 10.30$, $p < .01$. An additional test for practice effects in RTs again showed a main effect of half, $F(1, 11) = 8.75$, $p < .05$, but no indication for a modification of the correspondence effect by practice ($p > .5$).

Discussion

The results are very clear-cut: A substantial Simon effect was obtained even though stimulus features and response locations were again uncorrelated. As the only difference between the present experiment and Experiment 4 or Hasbroucq and Guiard's (1991) original experiment is related to the particular stimulus display, the disappearance of the Simon effect in the latter should not be due to S-R decorrelation. Instead, the evidence strongly suggests that stimulus-coding processes were the only determinant. Because the Simon effect requires that stimuli are coded as left or right, it disappears if the stimulus display does not allow for or suggest such a spatial coding. Presumably, this was the case in the experiment by Hasbroucq and Guiard and in Experiment 4, whereas the visual display structure in Experiment 5 counteracted the tendency to perceive incompatible S-R label pairings as single diagonals.

At this time, researchers do not know precisely which display factors are decisive for spatial coding and the perceptual organization of the stimulus field in a given task. Actually, this would presuppose a complete theory of (spatial) perception that is not yet available and certainly beyond the scope of this article. So, I can only speculate that the choice of rectangular stimuli prevented linewise grouping in Experiments 2 and 3, whereas the figure–ground relationship was critical in Experiment 5. Clearly, further research is needed to allow for more theoretically based predictions. Nevertheless, the perceptual-grouping hypothesis correctly predicts the outcome of Experiment 5 and provides a more consistent account of the available empirical evidence than that of Hasbroucq and Guiard (1991).

General Discussion

Five experiments investigated whether the Simon effect (i.e., faster responding with irrelevant spatial S-R correspondence) should be understood as an effect related to stimulus identification, as suggested by Stoffels et al. (1989) or Hasbroucq and Guiard (1991), or rather as a response-selection effect, as the traditional view would hold. Experiment 1 demonstrated that a Simon effect occurs even if there is no correlation between the relevant feature of the response-initiating stimulus (i.e., the color of the go signal) and response location. This finding rules out the perceptual account proposed by Hasbroucq and Guiard as well as their interpretation of their own findings (Experiment 2, color-to-color condition), which showed that the Simon effect disappears under specific experimental conditions.

The remaining experiments sought an alternative explanation for this disappearance. Experiment 2 examined whether the order in which participants scan the elements of a multielement stimulus might influence the size of the Simon effect. In different groups, either the stimuli or the response labels were much larger than the others, respectively. Although this salience manipulation can be expected to induce different scanning orders, Simon effects of the same size showed up in both groups, thus ruling out the scanning hypothesis.

Experiment 3 investigated whether the temporal characteristics of the warning signal might have played a critical role. The results, however, do not indicate any effect of the temporal overlap of warning signal and stimulus, ruling out the warning-signal hypothesis.

Experiment 4, an exact repetition of the original experiment, provided a full replication of Hasbroucq and Guiard's (1991) findings, thus showing that the disappearance of the Simon effect did not result from intertask transfer artifacts or from investigating too few participants.

Experiment 5 repeated Experiment 4, with a slightly modified stimulus display that was thought to render more salient the relative spatial position of stimuli. As expected, a substantial Simon effect was obtained, showing that Hasbroucq and Guiard's (1991) null effect has little to do with S-R correlation.

The findings of the present study have considerable implications for most of the current approaches to S-R compatibility effects. As has been repeatedly pointed out, the most important implications apply to the perceptual approach to the effect of irrelevant spatial S-R compatibility, as proposed by Stoffels et al. (1989) and Hasbroucq and Guiard (1991). The results of Experiments 1, 2, 3, and 5 demonstrate very clearly that the experimental decorrelation of stimulus feature and response location does not prevent a Simon effect. This is consistent with former findings of Simon et al. (1976) and Schulz (1993), who also reported Simon effects with decorrelation procedures, but it is especially damaging to the approach of Hasbroucq and Guiard.

The lack of empirical support for the Hasbroucq and Guiard (1991) account undermines their objections to classify the Simon effect and related effects of irrelevant location cues under the general heading of spatial S-R compatibility. The present findings strongly suggest a common basis of both effects of relevant and irrelevant spatial compatibility instead, just as proposed by Kornblum et al. (1990) and Prinz (1990), among others. Especially the results of Experiment 1 demonstrate that, in contrast to Hasbroucq and Guiard's claims, irrelevant location information is conveyed to the response-selection stage. This is in full agreement with psychophysiological evidence showing that, in noncorrespondence trials of a Simon task, activation of the incorrect response can precede activation of the correct one: Incorrect response preparation ipsilateral to irrelevant stimuli shows up, for example, in lateralized readiness potentials (Sommer, Leuthold, & Hermanutz, 1993) and subthreshold motor activity (Zachay, 1991). Obviously, the processing of location information does not stop at the stimulus-identification stage. Thus, in my view, the available evidence unequivocally points to the response-selection stage as the locus of the Simon effect. Spatial information, relevant or irrelevant to the task, automatically activates corresponding responses, thus producing facilitation, interference, or both, depending on which response the relevant stimulus information calls for.

The present results also have implications for attentional approaches to the Simon effect (Stoffer, 1991; Umiltà & Nicoletti, 1992). These approaches are based on the assumption that a stimulus is coded as left or right, depending on whether its analysis is preceded by a leftward or a rightward shift of spatial attention. On the one hand, this idea receives support from the results of Experiment 4 as well as from the original findings of Hasbroucq and Guiard (1991). According to the perceptual-grouping hypothesis, participants did not scan the stimulus displays but grouped the stimulus and the equally colored response label into a line-like figure on colored background. If so, no attention shift would have preceded the analysis of this imaginary line, thus preventing a Simon effect, according to the attentional approach. As this prediction is correct, the attentional approach is supported.

However, it would be very difficult to predict the results of Experiments 2, 3, and 5 from an attention-shifting approach. If participants had perceived the whole display as a single stimulus pattern, no Simon effect would be predicted, which is obviously not consistent with the data. If participants had scanned the display serially instead, the predictions of this approach would depend on the scanning order. Yet, this is not in line with the finding that the size manipulation in Experiment 2 was completely ineffective. In fact, the attentional approach would predict facilitation of the response that corresponds to the direction of the moving attentional focus when approaching the last to-be-scanned element. Suppose, for example, a left stimulus would appear, accompanied by two response labels. If the participants scanned the display in the order of stimulus, left response label, and right response label, then the last attentional shift would be rightward, so the right (noncorresponding!) response should be facilitated. If, however, the participants were able to restrict scanning to the stimulus and the same-color response label only, there would not even be an incompatible condition, because the last attentional shift would either be directed downward (with S-R correspondence) or its direction would correspond to the response location (with S-R noncorrespondence). Both predictions would be inconsistent with the data. Further problems arise from the finding of Experiment 3, that the temporal overlap between warning signal and stimulus does not affect the size of the Simon effect. As Proctor and Lu (1994) pointed out, an attentional approach would suggest a smaller effect with such an overlap. So, all in all, it does not seem possible to infer a prediction from the attentional approach that is plausible and consistent with the results of Experiments 2, 3, and 5 at the same time. As these are not the only problems the attentional approach to the Simon effect is confronted with (see Hommel, 1993c, 1994a, in press), it does not seem very helpful in understanding how spatial information intrudes into action planning—at least not in its current shape.

The present experiments strongly suggest that stimulus-coding processes play an important role in the emergence of compatibility effects or, as is presumably the case in Hasbroucq and Guiard's (1991) study, in their disappearance. Even though the stimulus display was rather similar in Experiments 3–5, the results differed dramatically. That is, apparently small differences in the physical world can induce a completely different cognitive representation of the situation. This is in full agreement with approaches to S-R compatibility emphasizing the cognitive representation of stimulus and response rather than their physical characteristics (Hommel, 1993a; Kornblum et al., 1990; Proctor et al., 1992) but runs counter to the expectations from approaches stressing physical properties of stimulus and response, such as the affordance account of Michaels (1993). However, it is also clear that the precise conditions for stimulus and response coding are largely unknown. As long as this is so, there will always be the need for post hoc hypotheses. Without additional theoretical assumptions on how, depending on which rules and conditions, stimuli and responses are and stay represented, cognitive accounts of S-R compatibility phenomena will remain incomplete.

Finally, it should be pointed out that Hasbroucq and Guiard's (1991) assumptions, although not applicable to the Simon effect, need not be completely invalid either. In fact, the general idea that response-related knowledge may play a role in the processing of stimulus information is in accordance with the more general theoretical approaches of Miller and Dollard (1941) and Postman (1955). Moreover, there are various demonstrations that learning to respond to a stimulus set affects discrimination performance on the same set in another task (see Cantor, 1965, for a review). One may also speculate that recent findings of cognitive influences on word perception (e.g., O'Hara, 1980; Prinzmetal, 1990) and object recognition (e.g., Hoffmann & Zießler, 1986) reflect influences of functional, action-related categories on perception, as already proposed by Ach (1921) and Heron (1957). Therefore, the considerations of Hasbroucq and Guiard may have their merits. These are, however, apparently not related to the effect of irrelevant spatial S-R compatibility.

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