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The relationship between stimulus processing and response selection in the Simon task: Evidence for a temporal overlap

Bernhard Hommel

Max-Planck-Institut für Psychologische Forschung, Leopoldstrasse 24, D-80802 München, Germany

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Summary. As is indicated by the Simon effect, choice reactions can be carried out faster when the response corresponds spatially to the stimulus, even if the stimulus location is irrelevant to the task. In Experiments 1–4 the relationships between the Simon effect and stimulus eccentricity, signal quality, and signal-background contrast are investigated. The Simon effect was found to interact with all of these factors, at least when manipulated blockwise. These results are at odds with previous results and are difficult to interpret from an additive-factor-method view. An alternative interpretation is suggested that attributes the results to the temporal relationship between the processing of the relevant stimulus information and stimulus location. The assumption is that a decrease in the Simon effect is caused by every experimental manipulation that markedly increases the temporal distance between the coding of the relevant stimulus information and that of the irrelevant stimulus location. This assumption was tested in Experiment 5 in a more direct way. The stimuli were built up on a screen over time, so that the temporal distance between the presence of location and identity information could be controlled experimentally. The results provide further support for a temporal-delay interpretation of interactions between irrelevant stimulus-response correspondence and factors that affect early stages of information processing.

Introduction

The speed of choice reactions is known to depend on the spatial relationship between stimulus and response. If, for example, a stimulus is presented on the left side of a display, it is responded to faster with a left-hand than with a right-hand response (e.g., Brebner, Shephard, & Cairney, 1972). This is the case even if stimulus location is completely irrelevant to the task (e.g., Simon & Rudell, 1967). While the effects of spatial correspondence are generally known as *spatial-compatibility effects*, the special case of an impact of irrelevant spatial stimulus–response correspondence is called the *Simon effect.* This phenomenon is closely related to the *accessory effect.* Accessory effects arise from spatial correspondence or noncorrespondence between the response and a lateralized distractor (to be ignored – e.g., auditory) that accompanies the centrally presented (e.g., visual) stimulus (Simon & Craft, 1970).

There have been repeated attempts to locate the Simon effect and the accessory effect within a hypothetical series of processing stages by application of the *Additive Factor Method* (AFM) suggested by Sternberg (1969). Following the logic of this method, it is concluded that two given task variables affect different stages when their statistical effects combine additively, while a statistical interaction of their effects is taken to indicate that they both affect a common stage in information processing.

The results of these AFM studies seem to be more or less clear. First, accessory or Simon effects have been shown to combine additively with variables that are assumed to influence early stages in information processing, namely stimulus quality and stimulus duration (Acosta & Simon, 1976; Simon, 1982; Simon & Berbaum, 1990; Simon & Pouraghabagher, 1978; Stoffels, Van der Molen, & Keuss, 1985). Second, correspondence effects combine additively with the effects of variables that presumably affect motor programming or later stages, such as response specificity, movement amplitude, and relative stimulus–response frequency (Stoffels, Van der Molen, & Keuss, 1989), as well as time uncertainty and accessory intensity (Stoffels et al., 1985). Mixed results have been obtained regarding the intensity of the accessory, which sometimes does interact with accessory location (Simon, Craft, & Small, 1970) and sometimes does not (Stoffels et al., 1985). Clear interactions have been found between correspondence effects and S–R mapping – that is, a variable related to response selection (Simon, Mewaldt, Acosta, & Hu, 1976; Stoffels et al., 1985).

Taken together, most of these results point to response selection as the locus of the Simon and of the accessory effects. Indeed, this view faces some problems arising from the fact that the accessory effect, instead of inter-

acting, combines additively with the response-selection-related effect of the number of response alternatives (Stoffels et al., 1989). On the one hand, this result might simply indicate that both factors affect different processes at a common response-selection stage. But it would also be consistent with the assumption that correspondence effects originate at an identification stage that directly precedes the response-selection stage (Sanders, 1990; Stoffels et al., 1989). However, apart from this issue, it seems fair to say that the effects of irrelevant location cues are thought to arise independently of processes located at rather early or rather late stages in information processing.

In the following, I shall not argue against this conclusion, but against its premisses. It will be shown that there is no justification in assuming that the Simon effect does not interact statistically with variables that affect early stages. Data will be presented in support of this argument, showing that under suitable experimental conditions the extent of the Simon effect does in fact depend on retinal eccentricity and the quality of the stimulus, on stimulus–background contrast, and on an experimentally induced temporal delay of identity information to location information.

From an AFM-based point of view, these results would indicate that irrelevant location cues affect all the stages between earliest pre-processing and response selection. This would of course be a somewhat odd conclusion, no matter what theoretical perspective is shared. While there is some debate as to whether these effects should be located at a response-selection, or rather at a stimulus-identification, stage (e.g., Hasbroucq & Guiard, 1991; Kornblum, Hasbroucq, & Osman, 1990), there is not a single approach that would assume any influence of spatial correspondence on more than one stage. However, I shall argue that such a conclusion is not necessary, and shall sketch how interacting effects of irrelevant spatial correspondence and early factors can still be reconciled with the assumption of a central location (e.g., at a response-selection stage) of the Simon effect. The cost of this suggestion is, however, that it implies a rejection of AFM interpretations of the empirical results obtained in Simon or related tasks when multiattribute stimuli (i.e., stimuli containing more than one informational aspect) have been employed. Thus, the theoretical conclusions from current approaches to the Simon effect may be right but – at least in the case of approaches based on AFM and linear-stage theory – for the wrong reasons.

Experiment 1: Stimulus eccentricity (randomized)

A first impetus for the present series of experiments arose from contradictory results obtained in several studies on the relationship between the Simon effect and stimulus eccentricity. Manipulations of retinal eccentricity in Simon tasks were carried out by Gunia (1987, Experiment 3), Nicoletti and Umiltà (1989, Experiment 2), and Zachay (1991). Further, Simon, Craft, and Small (1971) manipulated perceived eccentricity of auditory stimuli by varying phase differences of tones delivered binaurally through earphones. The results of these studies could not be more diverse: while Gunia and Simon et al. found a significant increase in the Simon effect with higher eccentricity, Nicoletti and Umiltà obtained a non-significant decrease, and Zachay found no indications at all of any interaction between eccentricity and spatial correspondence.

Some inconsistencies in these data may be explained by the specific stimulus arrangement used in these studies. Assume that a tone is presented with a virtual eccentricity of 15°, as in the Simon et al. (1971) study, or a visual stimulus appears only 0.3° from the position of a fixation point that was deleted 150 ms before, as in Gunia's experiment. With these display conditions it is very likely that at least some of the stimuli are spatially misperceived. If this were the case, some of the stimuli that are assumed to interfere would actually facilitate responses and vice versa. Suppose, for example, that a stimulus signalling a left-hand response is presented to the right of the fixation point with only little eccentricity. Then, if the stimulus were correctly perceived as a right-side stimulus, the response would be delayed. If, on the other hand, the stimulus were misperceived as being a left-side stimulus, the response would be facilitated. If this happened more often as eccentricity decreased, the results would mimic an interaction of spatial correspondence and eccentricity with correspondence effects increasing with eccentricity. Thus, a definite test of the relationship between stimulus eccentricity and the Simon effect requires that stimuli can be spatially well discriminated.

Experiment 1 was designed to meet these requirements. Here, a standard Simon task was employed with visual stimuli whose eccentricity varied randomly. Stimulus locations ranged from 0.2° to over 6° to allow for a large main effect of eccentricity. At the same time, spatial discriminability of stimuli was guaranteed by the presentation of a permanent vertical line that divided the display into a left and a right part. It was expected that this arrangement would preclude any increase in the Simon effect with eccentricity.

Method

Apparatus and stimuli. The experiment and data acquisition were controlled by a Rhotron VME system with an Atari high-resolution (640 × 400) monochrome monitor. Responses were made by the subject pressing the right or left SHIFT key of the computer keyboard with the corresponding index finger. From a viewing distance of approximately 60 cm, the subject saw a 13.25°-wide and 1.91°-high white field that was divided into two equal parts by a thin (0.03°) black vertical line. A solid black rectangle, 0.12° × 0.08° in size, superimposed on the dividing line, served as fixation point. The stimuli were a 0.38° × 0.38° solid black cross and a 0.29° × 0.29° solid black square, presented with low (0.19°), medium (3.05°), or high (6.10°) eccentricity to the left or right side of the median line.

Subjects and procedure. There were 14 women and 8 men aged 19–48 years who served as paid subjects. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Each subject served in a single session lasting about 40 min. A session was composed of 2 warming-up blocks and 30 experimental blocks. Each block consisted of 12 intermixed trials, whose type was defined by factorial combination of stimulus eccentricity (low, medium, or high), stimulus type (cross or square), and stimulus location (left or right).

The task was to press the left key in response to the square and the right key in response to the cross, as soon and as correctly as possible.

Table 1. Experiment 1: mean RTs (ms) and error percentages (in parentheses) for the three stimulus eccentricity conditions according to spatial S–R correspondence (C) and non-correspondence (NC). Effect sizes (NC-C) for each stimulus eccentricity are in the rightmost column

Eccentricity	C	NC	NC-C
Low	496 (2.1)	509 (1.7)	13
Medium	508 (1.1)	519 (2.1)	11
High	542 (3.6)	548 (3.2)	6

Each trial started, after an intertrial interval of 1,500 ms, with the presentation of the fixation point. After 1,000 ms the fixation point disappeared and the stimulus was presented. The stimulus was visible until the response was given, but not for longer than 1,000 ms. Presses on the wrong key were counted as errors, and trials with latencies exceeding 1,000 ms were considered as missing. Both kinds of trial were recorded and then repeated at some random position in the remainder of the block. In case they felt confused or distracted, subjects could delay the next presentation by keeping the key pressed down.

Results and discussion

Missing trials (<1%) were excluded from the analysis. Mean reaction times (RTs) and error percentages per subject, stimulus eccentricity, and correspondence condition were computed by averaging over the median RTs and rates, which were calculated for each combination of stimulus location and response location. The square roots of error percentages were employed for statistical analyses. In Table 1 mean correct RTs and error percentages are given as a function of stimulus eccentricity and spatial correspondence of stimulus and response.

RT and error data were analysed in a 3×2-factorial ANOVA design with Stimulus Eccentricity and Stimulus–Response Correspondence as within-subjects factors. First, Eccentricity had highly significant main effects on RTs, $F(2,42) = 52.81$, $p < .001$, and errors, $F(2,42) = 12.86$, $p < .001$, reflecting an increase in RT (From 503 to 514 to 545 ms) and in error rates with eccentricity. This effect comes as no surprise, considering the decrease in visual acuity towards the periphery. Second, the spatial Correspondence of stimulus and response had a significant main effect on RT, $F(1,21) = 5.92$, $p < .05$, but not on errors ($p > .6$), reflecting faster responses under correspondence (515 ms) than under non-correspondence (525 ms). This effect was also expected, since it only replicates the Simon effect. Third – and this is the most important result – the interaction of Eccentricity and Correspondence was not significant in the RT ($p > .4$) or error data ($p > .1$). While there was no indication of any interaction of Simon effect and stimulus eccentricity in the RT data, the error data were not so clear cut. There was indeed an unreliable tendency towards an interaction with comparatively fewer errors under non-correspondence than under correspondence in the low- and in the high-eccentricity conditions. But altogether, the data do not strongly suggest any dependence of the Simon effect on stimulus eccentricity.

However, the present data may underestimate such a relationship because of the non-blocked manipulation of the eccentricity variable. Owing to complete uncertainty about the eccentricity of the stimulus that would be presented next, the subject may have employed a special general-purpose strategy that would be used and be optimal only for intermixed presentations of stimuli at different eccentricities. For example, she or he may have distributed attention over the whole visual field to include even the most peripheral stimuli. This would reduce, or even eliminate, the need to shift the attentional focus onto the stimulus, a process whose duration increases with distance (e. g., Tsal, 1983). The result would be a diminished main effect of eccentricity, so that, as a consequence, an interaction of eccentricity and correspondence would be underestimated. Thus, to get a clear picture, it seemed useful to repeat the experiment with eccentricity varying only between, but not within, blocks.

Experiment 2: Stimulus eccentricity (blocked)

Method

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 1.

Subjects and procedure. There were 11 women and 11 men aged 19–32 years who served as paid subjects. Again, all had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. The procedure was almost identical to that in Experiment 1, except that here a session was composed of three randomly ordered sections, within which eccentricity (low, medium, or high) was held constant. Each of these sections included 4 warming-up blocks and 30 experimental blocks, each consisting of four intermixed trials, whose type was defined by factorial combination of stimulus type (cross or square) and stimulus location (left or right).

Results and discussion

Missing trials (<1%) were excluded from the analysis and the remaining data were treated as in Experiment 1. In Table 2, mean correct RTs and error percentages are given as a function of eccentricity and correspondence. In the RT data, the main effect of Eccentricity was again highly significant, $F(2,42) = 46.55$, $p < .001$, while the main effect of Correspondence (i. e., the Simon effect) just failed significance ($p > .06$). However, the Eccentricity × Correspondence interaction was highly significant, $F(2,42) = 9.67$, $p < .001$. Planned paired comparisons indicated that correspondence effects were very reliable within the low-eccentricity condition ($p < .001$, always two-tailed), but only marginal within medium- ($p < .07$), and completely absent from the high-eccentricity condition ($p > .4$). In the error data neither the effect of Eccentricity ($p > .1$), nor of Correspondence ($p > .7$), nor the interaction of both ($p > .2$) was significant.

As was indicated by the interaction of eccentricity and correspondence (now significant), the blocking of eccentricity manipulations actually was effective in revealing a dependence of the Simon effect on stimulus eccentricity. The fact that the main effect of stimulus eccentricity is now more than twice as large as in Experiment 1 gives some credit to the assumption that the blocking of eccentricity enables the employment of more specialized strategies

Table 2. Experiment 2: mean RTs (ms) and error percentages (in parentheses) for the three stimulus eccentricity conditions according to spatial S–R correspondence (C) and non-correspondence (NC). Effect sizes (NC-C) for each stimulus eccentricity are in the rightmost column

Eccentricity	C	NC	NC-C
Low	485 (1.9)	508 (2.8)	23
Medium	534 (3.3)	545 (2.9)	11
High	600 (2.8)	595 (2.5)	–5

than random presentation does. While the present data do not allow a more precise description of the way the blocking manipulation affected information processing, they do allow the following three conclusions.

First, the hypothesis under test was that there is no increase of the Simon effect with higher eccentricity when good spatial discriminability of the stimuli is provided. Since neither of the present experiments gave evidence of a positive relationship between eccentricity and the Simon effect's extent, the hypothesis is clearly supported. Thus, the findings of Gunia (1987) and Simon et al. (1971) may well have resulted from mislocations of stimuli under low eccentricity.

Second, a factor that can be assumed to affect a very early pre-processing stage (Sanders, 1990) can be shown to interact with a factor localized two (Stoffels et al., 1989) or three (Sanders, 1980) stages further. This is, of course, surprising from an AFM viewpoint because it would suggest a common processing stage affected by both stimulus eccentricity and irrelevant spatial stimulus–response correspondence. This conclusion stands in a striking contrast to the results of AFM studies already mentioned in the Introduction.

Third, a comparison of Experiments 1 and 2 seems to suggest that the relationship between the effects of stimulus eccentricity and of spatial correspondence has been modified by the blocking manipulation. This impression is confirmed (although with somewhat weak reliability) by the results of an ANOVA that was run over the subjects of both experiments with the random/blocked manipulation as a between-groups factor. Here, the three-way interaction of Blocking, Eccentricity, and Correspondence was marginally significant, $F(2,84) = 2.76$, $p < .07$. This result is not easy to handle from an AFM approach because it suggests a violation of its underlying stage-robustness assumption, which claims that the relation between two given variables should not depend on any interaction of one of these with a third one (Sanders, 1990).

Though the results obtained so far are interesting and allow some unexpected conclusions, they nevertheless call for an explanation. While it was predicted and expected that the Simon effect does not grow with stimulus eccentricity, the reverse finding of a negative relationship is surprising, and in fact somewhat counterintuitive. Why should the impact of spatial-stimulus information diminish with increasing distinctiveness? Should we really assume that eccentricity and irrelevant spatial correspondence influence a common information-processing stage? Let us try to answer these questions on the basis of some considerations that concern the temporal relationship between the processing of the relevant and irrelevant information in a Simon task.

Theoretical considerations

In essence, the Simon effect is usually considered to arise from a conflict between two internal codes, one of which is related to the task-relevant information of the stimulus, while the other is related to the irrelevant stimulus location. As has already been mentioned, it is, however, far from being settled what kind these codes are and how they interact. For example, they were assumed to be response codes activated by both kinds of stimulus information (Wallace, 1971), or representations of the two kinds of information that either compete at a proposed stimulus-identification stage (Hasbroucq & Guiard, 1991; Stoffels et al., 1989) or bias a further (e.g., attentional or selection) process (Simon, Acosta, Mewaldt, & Speidel, 1976). Since the validity of the following arguments does not in any way depend on which of these views is correct, or on whether they are different at all, we shall refer only to a relevant and an irrelevant code, both of which cause or come into some kind of conflict in cases of spatial non-correspondence between stimulus and response.

Consider how manipulations of stimulus eccentricity affect the time of formation for the relevant and the irrelevant codes. Since for visual stimuli retinal acuity decreases with eccentricity, analysis of the relevant information will be increasingly hampered the more peripherally the stimulus is presented. That is, eccentricity delays the formation of the relevant code, be it a stimulus or a response code. This delay can be considerable, as is indicated by the range of eccentricity effects from 42 ms in Experiment 1 to 101 ms in Experiment 2.

There will be a twofold effect of retinal eccentricity on the formation of the irrelevant code. On the one hand, analysis of location information could also be somewhat delayed by decreasing visual acuity. However, data from both stimulus-detection (Poffenberger, 1912) and spatial-discrimination tasks (Rabbitt, 1967) suggest that an acuity-dependent delay of localization is much smaller than the delay that has to be assumed for stimulus identification. On the other hand, the formation of the irrelevant code should be facilitated by higher eccentricity because of enhanced spatial discriminability (Rabbitt, 1967). That is, a possible acuity-dependent delay in the formation of the irrelevant code should be overcompensated by discrimination-dependent facilitation.

If it can be plausibly assumed that the formation of the irrelevant location-dependent code normally precedes the formation of the relevant code, we can conclude that increasing eccentricity increases the temporal advantage of the irrelevant to the relevant code. It may have been this influence on the temporal relationship between the formation of the relevant and the irrelevant codes that led to the present results. At first sight it seems counterintuitive to suppose that a code's greater temporal advantage should decrease its influence on further processing operations. But consider how a conflict of a kind indicated by the Simon effect could be solved. Either the irrelevant and conflicting

code decays over time; in this case the conflict can be settled by awaiting a sufficiently low activation level of the code compared to the level of the relevant code (cf. e.g., Morton, 1969; Van der Heijden, 1981). Or the conflict has to be settled by active inhibition of the conflicting code (Lowe, 1979; Neill & Westberry, 1987; Tipper, MacQueen, & Brehaut, 1988). In order to explain the present results we need not decide between these types of models, because all varieties allow the same prediction: the greater the temporal advantage of the irrelevant code, the smaller is its influence. This follows from a passive-decay model, since the later the relevant code comes up, the weaker the competing irrelevant code is, owing to its steady decay. From an active-inhibition model, the same prediction must be made. The earlier the irrelevant code is built up, the earlier an inhibition process can be initiated – that is, the weaker the irrelevant code is when the relevant code is formed.

With this interpretation a more general rule can be derived. The Simon effect can be reduced by the choice of experimental manipulations that increase the temporal lag between the formation of the location-related irrelevant and the relevant codes (either by selective delay in the formation of the relevant code and/or by the speeding up of the formation of the irrelevant code). This rule is consistent not only with our own results, but also with the findings of McCann and Johnston (1992), Simon, Acosta, Mewaldt, and Speidel (1976) and of Umiltà and Liotti (1987). In the first two studies, the Simon effect was eliminated by the responses of the subjects being delayed by 200 ms or more by means of an interpolated secondary task. Umiltà and Liotti (1987) varied the side and the relative position of the stimulus and provided information about one or the other of these factors before the stimulus was presented. They found that Simon effects were related only to the non-cued spatial relationship. These studies suggest that the irrelevant code decays over time, thus losing impact on response selection (or stimulus identification)[1]. That is, the effects of irrelevant spatial information depend on the temporal contiguity of spatial coding and response selection, as was already supposed by Umiltà and Liotti (1987).

To be sure, while the validity of the temporal-delay hypothesis does not depend on a specific theory about the kind of critical codes, precise empirical predictions can be made only on the basis of such a theory. For example, if the critical codes were stimulus codes, the delaying of the formation of a response code would probably have no influence on the extent of the Simon effect. But since up to now the Simon effect has in no case been assumed to arise before stimulus identification, a number of predictions – in some cases surprising ones – can nevertheless be made, some of which were tested in the experiments presented in the following.

Experiment 3: Signal quality

A prediction that is particularly surprising (and of special interest for a linear-stage-model approach to information processing) is that of an underadditive influence of signal quality on the Simon effect. This prediction follows from our considerations, because the degradation of stimuli should hamper identification, while localization should be more or less unimpaired. That is, the Simon effect should be more pronounced with intact, than with degraded, stimuli because an intact stimulus can be assumed to be coded faster, so that its code would be temporally less delayed in relation to the location code than the code of a degraded stimulus would be. This prediction is surprising, as it seems to be refuted by the results of Simon and colleagues (Acosta & Simon, 1976; Simon, 1982; Simon & Pouraghabagher, 1978) and of Stoffels et al. (1985), who found no such interaction in studies on the accessory effect. However, for several reasons, these data do not provide sufficient evidence against our hypothesis.

First, there is a somewhat formal argument. Up to now, signal quality has been manipulated in accessory tasks only, with centrally presented visual stimuli accompanied by lateralized auditory stimuli. That is, strictly speaking, data on the relationship between stimulus quality and the Simon effect are not available. Thus, it is open to question whether additivity between stimulus quality and spatial correspondence can also be found in a standard Simon task.

Second, there are always many possible causes for the occurrence of a null effect, that may or may not be theoretically interesting and may or may not lead us to assume that the factors affect different stages (e.g., Prinz, 1972; Taylor, 1976). There can be no doubt that, while the lack of a statistical interaction effect may be taken as a first indication of an additive relationship between two variables, it is certainly not a definite proof.

Third, and more specifically, a non-significant interaction may result from varying the levels of the factors in question only within a small range of values. Thus, interaction effects may be obscured by a lack of "operating space," as Sanders (1980) put it. A comparison of Experiments 1 and 2 may serve as an example. While the main effects of stimulus eccentricity were clearly significant in both experiments, only Experiment 2 revealed an interaction, based on a main effect more than twice as large as that in Experiment 1. However, even in Experiment 1, a main effect of 46 ms was still obtained – which does not lie too far from the 57–76 ms range of the significant signal-quality main effects in the available studies cited above[2]. It is obvious to assume that if a main effect of this size did not provide enough operating space in Experiment 1, then the main-effect sizes in the signal-quality studies may also have been insufficient.

Thus, altogether, it remained to be seen whether the Simon effect would turn out strong enough to survive even more drastic manipulations of stimulus quality than the method hitherto applied, of obstructing the view by plexi-

[1] The last two of these studies also show that the Simon effect does not simply disappear as a consequence of a general increase in the overall RT level. In the Simon et al. study, the largest effects were connected to the highest overall levels. Umiltà and Liotti (1987, Experiment 5) found that the precueing of all spatial relationships produced the fastest responses, while the Simon effect disappeared.

[2] I have disregarded the data of the elderly subjects of Simon and Pouraghabagher (1978), whose average of 73 years does not permit a direct comparison with the performance of student populations.

glas. In the present study, letter stimuli were used that were in some conditions partly masked by more or less complex patterns. In addition, detection trials were employed before and after each Simon task in order to estimate the effect of signal quality on the processing of the irrelevant stimulus-location information. Of course, a detection task does not permit a pure measurement of the duration of location processing, because the response does not depend on location information. It was nevertheless preferred to other tasks with spatially defined response criteria, because these would have very likely drawn attention to stimulus location in the Simon task, too. Therefore, our inferences as to the temporal relationship between the processing of relevant and irrelevant stimulus information are based on somewhat indirect measures. However, it seems plausible that the effect of stimulus degradation on detection can at least be compared better with its effect on localization than on letter identification.

Method

Apparatus and stimuli. The apparatus was identical to that in Experiment 1. The subject saw a 4.20°-wide and 1.72°-high field that either remained white to provide high stimulus quality or was overlaid with an evenly structured grey pattern to provide medium quality, or with a complex black-and-white pattern to provide low quality. A $0.29° \times 0.19°$ black cross served as fixation point. The stimuli were the capital letters T and I, subtending $0.19° \times 0.33°$ in space. They were presented 1.53° to the left or right side of the median plane.

Subjects and procedure. There were 16 women and 6 men aged 19–34 years who served as paid subjects. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Each subject served in a single session lasting about 40 min. A session was composed of three randomly ordered pattern sections, within which the pattern of the background field, and thus the stimulus quality, was held constant. Each of these sections consisted of an initial detection block, the binary-choice (i. e., Simon) task, and a final detection block. Throughout the whole experiment, the mapping of stimuli to response keys (T = left, I = right) was held constant.

Each pattern section began with an *initial detection block.* The subject was told only to respond with the left (or right) response key to the onset of the stimulus, which was the letter T (or I), according to the letter-key mapping in the binary-choice task. This letter was presented randomly five times on the left side and five times on the right side. The procedure was then repeated for the other response. After the detection block, the subject performed the *binary-choice task.* This task included 2 warming-up blocks and 20 experimental blocks, each consisting of four intermixed trials, whose type was defined by factorial combination of stimulus letter (T or I) and stimulus location (left or right). After the choice task, a *final detection block* was run. It was identical to the initial detection block, but had the order of responses reversed.

Results and discussion

Missing trials (<1%) were excluded from the analysis. Choice-reaction data were treated in the same way as in the preceding experiments and detection data were pooled over both detection blocks. First, it was checked whether the experimental manipulation of signal quality did affect the coding of relevant and irrelevant stimulus aspects differently. So median RTs for detection and choice trials were averaged over stimulus location and response location and then analysed by means of a 3×2-factorial ANOVA with Signal Quality and Response Type as within-subjects factors. The main effects of Response Type, $F(1,21) = 208.48$, $p < .001$, and Signal Quality, $F(2,42) = 84.03$, $p < .001$, were highly significant, as well as the interaction of Response Type and Signal Quality, $F(2,42) = 14.29$, $p < .001$. The latter effect indicates that choice reactions were much more impaired by the reduction of signal quality than were simple reactions. While simple reaction times increased by 91 ms from 366 ms with high stimulus quality to 380 ms with medium, and 457 ms with low quality,[3] choice-reaction times increased by 193 ms: from 549 ms with high to 568 ms with medium, and to 742 ms with low stimulus quality. Thus, there is evidence that the reduction of stimulus quality delays the formation of the relevant stimulus code more than the formation of the irrelevant code.

Table 3. Experiment 3: mean RTs (ms) and error percentages (in parentheses) for the three signal-quality conditions according to spatial S–R correspondence (C) and non-correspondence (NC). Effect sizes (NC-C) for each signal-quality block are in the rightmost column

Signal quality	C	NC	NC-C
High	541 (1.9)	558 (3.1)	16
Medium	563 (2.9)	572 (3.9)	10
Low	755 (19.3)	730 (15.4)	–24

As in Experiments 1 and 2, a 3×2-factorial ANOVA was run, with Signal Quality and Stimulus–Response Correspondence as within-subjects factors. Table 3 shows mean correct RTs and error percentages as a function of signal quality and correspondence. Signal Quality had a highly significant main effect on RTs, $F(2,42) = 102.94$, $p < .001$, and on errors, $F(2,42) = 40.27$, $p < .001$. Responses were slower and errors more frequent in conditions with reduced stimulus quality, that is, 549 ms and 2.5% with high, 568 ms and 3.4% with medium, and 742 ms and 17.4% with low quality. The main effect of Correspondence (i.e., the Simon effect) fell far from significance for both, RTs ($p > .9$) and errors ($p > .5$). However, the interaction of Signal Quality and Correspondence was clearly significant for RTs, $F(2,42) = 5.13$, $p < .01$, and errors, $F(2,42) = 4.40$, $p < .05$.

Planned paired comparisons indicated that correspondence effects were reliable in the RT data only within the high-quality condition ($p < .05$, always two-tailed), but absent from the medium- ($p > .1$) and low-quality conditions ($p > .1$). In the third condition, the significance criterion (which would have indicated a reversed correspondence effect!) was missed mainly because of extreme positive Simon effects in two subjects (99 and 133 ms), who started

[3] As one of the reviewers pointed out, these times are much higher than one would expect for real simple reaction times. My guess is that the fast and frequent succession of simple and choice reactions – originally chosen for optimal comparability – resulted in an often insufficient preparation of the subject for the detection task, so that subjects may have often or always tried to identify the stimuli before responding. But note that by perhaps obscuring, rather than revealing, differences between the detection and the choice tasks, our design has been conservative in working against the hypothesized interaction of signal quality and response or task type.

the experiment with this very condition. The RT pattern was more or less mirrored in comparisons of the error percentages. Correspondence effects were significant (with reversed direction!) in the low-quality condition only, but completely absent from medium ($p > .1$) and high stimulus-quality conditions ($p > .1$).

The results are clear cut. It is obvious that decreasing stimulus quality eliminated the Simon effect in the RT data. This was predicted, because degradation should impair identification more than localization, resulting in a comparably larger temporal lag of the relevant code in the condition with poor signal quality. A larger lag should in turn result in a reduced conflict between the relevant and the irrelevant codes, because the leading irrelevant code should have been either more decayed or more inhibited at the time the relevant code showed up.

As has already been mentioned, we have no direct evidence to support the assumption of different effects of signal quality on the timepoint of formation of the relevant and the irrelevant codes. However, indirect evidence is given by a comparison of the data from the detection and the binary-choice tasks. Here, signal quality affected the identification-dependent task more than the detection-dependent task, so that it seems plausible that there would be a more pronounced effect of signal quality on identification than on localization.

Our results are not compatible with the findings of Acosta and Simon (1976), Simon (1982), Simon and Pouraghabagher (1978), and Stoffels et al. (1985), who failed to obtain a significant interaction between stimulus quality and spatial correspondence of a so-called accessory stimulus. However, in Experiment 3, the main effect of stimulus quality amounted to 214 ms, which is two to three times as much as in the studies of Simon and colleagues and of Stoffels et al. Thus, as has already been pointed out, the available null effects may very well have resulted from the manipulation of signal quality within a range that was too small to give rise to marked influences on the correspondence effect.

Finally, a word should be said about the somewhat odd finding that stimulus-corresponding responses were slower and more prone to errors than non-corresponding ones in the low-quality condition. Though only reliable for error rates, this pattern very much resembles the results of Experiment 2 with high eccentricity. Such a result pattern would be predicted by an inhibition model, which proposes that code conflicts are solved by inhibition of the irrelevant or wrong code (see Lowe, 1979; Neill & Westberry, 1987; Tipper et al. 1988). Suppose that inhibition of the irrelevant location code and/or the corresponding response always began soon after code formation, so that a large temporal advantage resulted in a comparably high degree of inhibition. For example, the presentation of a right-side stimulus would result in inhibition of the right response (or a related code). If a late-arriving relevant code were to propagate the same response, which is the case under stimulus–response correspondence, the correct response would already be inhibited and, consequently, be more delayed than under stimulus–response non-correspondence. In other words, given a large lag of the relevant code, the non-correspondence of stimulus and response would allow for faster responses than correspondence would. From this perspective the present results seem to make sense. However, since the inhibition-related results were statistically reliable in one case only, it should be left to further empirical research to test whether these speculations hold.

Experiment 4: Signal contrast

The results of Experiment 3 nicely demonstrate an interaction between the Simon effect and a rather early factor. Signal quality is commonly assumed to affect a stage of feature extraction (Sanders, 1990) or stimulus encoding (Stoffels et al., 1989), which is succeeded by an identification stage and a response-selection stage. Since irrelevant location cues are thought to affect either the identification stage (Stoffels et al., 1989) or the response-selection stage (Acosta & Simon, 1976), our results seem to be a problem for a pure AFM-based approach. We either have to propose that signal quality in fact affects both the feature-extraction and the identification or response-selection stages, or we are forced to suspect that irrelevant spatial correspondence affects feature extraction.

The purpose of Experiment 4 was to push our argument a little further in demonstrating an underadditive interaction of irrelevant spatial correspondence with signal contrast – that is, with a factor that is assumed to affect exclusively a very early pre-processing stage (Sanders, 1980, 1990). The expectation that such an interaction can be demonstrated is not as hopeless as may seem at first sight. On the one hand, Experiment 2 gave rise to an underadditive interaction of spatial correspondence and retinal locus, the latter still being a factor also commonly thought to affect pre-processing exclusively. On the other hand, Stanovich and Pachella (1977) were able to show an underadditive interaction of signal contrast and (even if non-spatial) stimulus–response compatibility (digit naming vs. button-pressing), just as our temporal-delay hypothesis would have predicted. Thus, in Experiment 4, it was expected that the Simon effect would decrease under low, compared to high, signal contrast.

Method

Apparatus and stimuli. The stimulus presentation and data acquisition were controlled by a Hewlett Packard Vectra RS20 computer. Stimuli were presented on an Eizo VGA monitor. Responses were given by pressure on the left or right SHIFT key of the computer keyboard with the corresponding index finger. A $0.29° \times 0.29°$ asterisk served as fixation point. The capital letters X and Y served as stimuli, each subtending $0.29° \times 0.57°$ in space. They appeared 0.70° to the left or right of the central fixation point. The fixation point was white (29 cd/m^2), and the background was almost black (5 cd/m^2). The stimuli were of either a bright (27 cd/m^2) or a dark (6 cd/m^2) grey, depending on the contrast condition.[4]

[4] Even though this kind of manipulation confounds signal-background contrast with stimulus intensity, it was preferred because contrast has been operationalized in this way in most AFM studies (e.g., Sanders, 1980; Shwartz, Pomerantz, & Egeth, 1977; Stanovich & Pachella, 1977). As signal intensity is assumed to affect the same (pre-processing) stage as signal contrast (Van Duren & Sanders, 1988) anyhow, this confounding should not be critical for the interpretation of our results.

Subjects and procedure. Eight women and seven men aged 20–38 years served as paid subjects. Again, all had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Each subject served in a single session lasting about 25 min. A session was composed of two randomly ordered contrast sections, within which stimulus luminance – and therefore contrast – was held constant. Each section consisted of 50 four-trial blocks resulting from randomized combinations of two stimuli and two spatial positions. The first 20 blocks were considered as training blocks and were not analysed.

The experiment took place in a dimly lit room. Subjects were instructed to press the left-hand key in response to the letter X and the right-hand key in response to the letter Y. In each trial, the sequence of events was as follows. After an inter-trial interval of 1,500 ms, the fixation point was presented for 500 ms. Then, following a blank interval of 500 ms, the stimulus appeared at the left or right spatial position and stayed on the screen until a response was given, but for no longer than 1,500 ms. Responses with the wrong key were counted as errors and responses with latencies above 1,500 ms were considered as missing. Both kinds of trial were recorded and then repeated at some random position in the remainder of the block. Subjects could delay the next trial by keeping the key pressed down in case they felt confused or distracted.

Results and discussion

The data were treated as in the preceding experiments. Missing trials (<1%) were excluded from the analysis. A 2×2-factorial ANOVA was run, with Contrast and Stimulus–Response Correspondence as within-subjects factors. Table 4 shows mean correct RTs and error percentages as a function of contrast and correspondence. Contrast had a highly significant main effect on RTs, $F(1,14) = 55.22$, $p < .001$, and on errors, $F(1,14) = 5.25$, $p < .05$. Responses were slower and errors more frequent under low contrast (609 ms, 5.6%) than under high contrast (486 ms, 2.4%). Correspondence had a highly significant main effect on RTs, $F(1,14) = 21.41$, $p < .001$, but not on errors ($p > .39$). That is, responses were slower under non-correspondence (560 ms) than under correspondence (535 ms), while the error rates were similar in both conditions (3.7% and 4.3%, respectively). Finally, the interaction of Contrast and Correspondence was significant for RTs, $F(1,14) = 6.00$, $p < .05$, but not for errors ($p > .73$). As is shown in Table 4, correspondence affected responses more under high than under low contrast.

Altogether, the results are as expected, demonstrating a decreased Simon effect under low signal contrast. Spatial stimulus correspondence and signal contrast can therefore be shown to interact underadditively. This resembles the findings of Stanovich and Pachella (1977), who varied compatibility by comparing naming with button-pressing in response to digits. The explanation given by Stanovich and Pachella is also very similar to ours in proposing a temporal overlap of stages related to stimulus identification and response operations. However, some objections to their findings, as well as to their conclusions, have been raised from the point of view of AFM and serial-stage theory.

Sanders (1980) encountered the approach of Stanovich and Pachella (1977) as follows: he pointed out that in studies that showed additive effects of compatibility and signal contrast, main effects in the range of 25–40 ms were obtained, while Stanovich and Pachella had observed 100–200 ms. Contrast effects of this degree may indicate a near-threshold condition under low contrast, so that the response-selection stage may have received distorted signals under low, as compared to high, contrast. Thus, while a normal compatibility effect could occur under high contrast, the response compatibility of the stimulus would not be worth much under low contrast, because it is only incompletely delivered to the response-related stages. The result would be an underadditive interaction of compatibility and contrast, just as was obtained.

Table 4. Experiment 4: mean RTs (ms) and error percentages (in parentheses) for high and low signal-background contrast according to spatial S–R correspondence (C) and non-correspondence (NC). Effect sizes (NC-C) for each contrast condition are in the rightmost column.

Contrast	C	NC	NC-C
High	470 (2.5)	502 (2.3)	32
Low	600 (6.0)	619 (5.2)	19

While a stage-theoretical explanation along these lines can well handle the results of Stanovich and Pachella without an overlapping-stage assumption, the present experiment does not allow such an argumentative strategy. On the one hand, there is Sanders's (1980) observation that small main effects of contrast were accompanied by additivity of compatibility and signal contrast, while large effects were connected to interactions. This fits nicely with our finding that interactions of spatial correspondence with stimulus eccentricity and signal quality seem to occur together only with main effects of the order of 100 ms or more. In Experiment 4, the main effect of contrast was also in the range of Stanovich and Pachella's. On the other hand, this is no valid argument in the present context. While it cannot be ruled out that the speed of localization would suffer somewhat from low contrast, it is implausible to suspect that a contrast manipulation would lead to a distortion of irrelevant spatial information while the relevant information is still delivered sufficiently undistorted to permit correct responding. As our error rates in the range of 2% to 6% demonstrate, the relevant information about letter identity was easily extractable from the display, even under low contrast, although this was obviously more time-consuming. Since, under low contrast, identification should suffer more than localization, the delivery of an undistorted spatial signal seems highly plausible. Thus, the results of Experiment 4 obviously pose further problems for an approach based on AFM logic.

Experiment 5: Delay in stimulus formation

The preceding experiments demonstrated statistical interactions of irrelevant spatial stimulus–response correspondence with factors assumed to affect early and even very early stages of information processing. While these results fit our temporal-delay hypothesis nicely, its core assumption, stating that it is the temporal relationship between relevant and irrelevant information that is responsible for our findings, has been tested somewhat indirectly. In particular, we attempted to influence the temporal course of

the relevant information by means of slowing down its processing at several more or less early processing steps. This should increase the temporal advantage of the irrelevant spatial information, so that its decay or inhibition can start earlier. The assumption was that the earlier the decay or inhibition starts, the weaker the irrelevant code should be at the time the relevant code shows up.

In Experiment 5, the temporal relationship between the relevant and the irrelevant codes was manipulated much more directly than in the preceding experiments. An attempt was made to separate relevant and irrelevant information without the presentation of two different stimuli or of stimuli in two different modalities, as is usually the case in investigations of the accessory effect. This was done by employing a stimulus-formation-delay technique that permitted stimulus presentation over time – that is, some of the stimuli in Experiment 5 appeared only gradually. Through this, the temporal relationship between relevant and irrelevant stimulus information underlay strict experimental control, since the delay of the relevant in relation to the irrelevant information could be easily manipulated by extension of the formation delay. As soon as the first part of a stimulus appeared, the subject was able to register its position. However, its identity could be detected only after sufficiently distinctive information had been presented.

Two conditions were contrasted. In the *immediate* condition, the stimuli appeared at once. In the *delay* condition, the formation of the stimulus extended over time, so that the relevant information about stimulus identity was present only after 196 ms had elapsed, while the irrelevant spatial information was available immediately. In other words, the relevant identity information was or was not delayed as compared to the irrelevant spatial information by 196 ms. The predictions are straightforward. As our hypothesis proposes a decrease in the correspondence effect with an increasing temporal advantage of the irrelevant spatial information, the Simon effect should be larger in the immediate condition than in the delay condition.

Method

Apparatus and stimuli. The apparatus was the same as in Experiment 1. The subject saw a 3°-wide and 1.38°-high white field. A central 0.29° × 0.19° black cross served as the fixation point. The stimuli were the capital letters U and D, subtending 0.19° × 0.38° in space. They were presented 0.57° to the left or right side of the median plane. In the immediate-formation condition, the given stimulus letter was presented on the screen at once. In the delayed-formation condition, however, the stimulus built up gradually within 196 ms. Before completion, no letter-identity information was available – that is, a U was not discriminable from a D during the formation period.

To achieve this, an overlap stimulus was constructed, consisting of only those pixels that overlapped in the pixel representations of the two stimulus letters. The resulting stimulus consisted of 45 pixels. At the beginning of each of the first 14 refresh cycles of the Atari screen (which is refreshed approximately every 14 ms), three to four randomly chosen pixels of the overlap stimulus were presented. So, all the pixels contained in both stimuli (i. e., the overlap stimulus) were visible 182 ms after the presentation of the very first pixels. At the beginning of the following 15th cycle, the remaining pixels were presented, so that the complete stimulus was now visible.

Subjects and procedure. Eight women and eight men aged 19–39 years served as paid subjects. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Each subject served in a single session lasting about 30 min. A session was composed of two randomly ordered delay sections. Each of these included 2 warming-up blocks and 40 experimental blocks, each consisting of four intermixed trials, whose type was defined by factorial combination of stimulus (U or D) and stimulus location (left or right).

After an inter-trial interval of 1,500 ms the fixation point was presented for 500 ms. After another blank interval of 1,000 ms the stimulus was presented. In the immediate condition, the stimulus appeared at once. In the delay condition, the stimulus appeared gradually within 196 ms. The stimulus stayed on the screen until a response was given, but not for longer than 1,000 ms. Response time was defined as the time that elapsed between the presentation of the distinctive stimulus pixels (i. e., letter-identity information) and the key press. Subjects could delay the next trial by keeping the key pressed down if confused or distracted.

Table 5. Experiment 5: mean RTs (ms) and error percentages (in parentheses) for immediate and delayed formation of relevant relative to irrelevant stimulus information according to spatial S–R correspondence (C) and non-correspondence (NC). Effect sizes (NC-C) for immediate and delayed formation are in the rightmost column

Stimulus formation	C	NC	NC-C
Immediate	427 (2.5)	459 (3.5)	33
Delayed	466 (2.8)	485 (4.3)	18

Results and discussion

The data were treated as in the preceding experiments. Missing trials (<1%) were excluded from the analysis. The main effect of Correspondence was highly significant for RTs, $F(1,15) = 52.26$, $p < .001$, but only marginally significant for error rates, ($p < .08$). The main effect of Formation Delay was highly significant for RTs, $F(1,15) = 15.62$, $p < .001$, and significant for errors, $F(1,15) = 5.29$, $p < .05$. The interaction of Correspondence and Delay was significant in the RT data, $F(1,15) = 5.64$, $p < .05$, but not in the error data ($p < .48$).

Again, the results are clear, and consistent with our predictions. They show an underadditive interaction of delay and irrelevant spatial correspondence: that is, the Simon effect decreases with increasing temporal advantage of location information. This conclusion is further supported by the finding that both the Simon and the accessory effects are reduced, or even eliminated, when the stimulus location is either validly cued or held constant over several trials (Simon & Acosta, 1982; Simon & Rudell, 1967; Stoffer, 1991; Umiltà & Liotti, 1987; Verfaellie, Bowers, & Heilman, 1988). Indeed, in some sense, the only difference between these studies and the present experiment is that spatial cue and stimulus were identical in the latter, but not the former, case.

Conclusions

Five experiments were performed demonstrating underadditive interactions of irrelevant spatial stimulus–response correspondence with factors that are assumed to affect more or less early stages of information processing. Such interactions could be shown for stimulus eccentricity (reti-

nal location), signal quality, and signal contrast. Following the logic of AFM, this would mean that the correspondence effect must be simultaneously located at a feature-extraction stage and at a pre-processing stage. Note that this conclusion follows despite data that show additive relationships between some of these early factors and spatial correspondence. As has already been conceded by Sternberg (1969), the lack of a statistical interaction does not necessarily indicate that the given factors affect different stages. Conversely, they may affect the same stage, but different processes, or the main effect(s) may have been too small because of insufficient variation in the factor levels. To reveal such hidden interactions, it is recommended either that a further variable be added or that the experiment be repeated, with larger differences between the factor levels, to see whether the relationships between the variables in question remain unchanged (Sanders, 1980). We followed this advice and found that the relationships did in fact change.

In a comparison of Experiments 1 and 2, the blocking manipulation changed the additive relation of correspondence and eccentricity into an interactive relation, although with only weak statistical reliability. Furthermore, Experiment 4 showed that an interaction of stimulus quality and spatial correspondence was revealed when a main effect of signal quality was provoked that was larger than in the studies of Acosta and Simon (1976), Simon (1982), Simon and Pouraghabagher (1978), and Stoffels et al. (1985), who all found additivity. Should we then conclude that irrelevant spatial correspondence affects all the stages from earliest pre-processing to stimulus identification and perhaps to response selection? How can we avoid a positive answer that would, of course, lead to a theoretically meaningless universal model?

The solution suggested here refers to the temporal relationship between the formation of internal codes of the relevant and the irrelevant stimulus information. The proposed temporal-delay hypothesis assumes that every experimental manipulation that markedly increases the temporal distance between the formation of the relevant stimulus code and the irrelevant spatial code leads to a decreased Simon effect – that is, to a smaller effect of irrelevant spatial correspondence between stimulus and response. This hypothesis is quite general, and theoretically neutral. In particular, its validity does not depend on whether the Simon effect is understood as indicating a problem of stimulus identification or response selection – if one chooses to draw a line between these processes at all; nor does it depend on a specific model of the mechanism that ensures that the right code wins most of the time. Nevertheless, it allows for the derivation of several unexpected predictions, some of which were tested successfully.

The temporal-delay hypothesis is fully compatible with the Asynchronous Discrete Coding model proposed by Miller (1982, 1988). He assumes that in the case of multi-attribute stimuli, one attribute may be coded and transmitted to the following stages before the coding of the other attributes is completed. In the present context, this implies that activities at a later stage (e. g., response selection or stimulus identification) may be initiated by the location code, even though some work at earlier stages (e. g., pre-processing or encoding of the relevant stimulus attribute) remains to be done.

From this perspective, our results provide no evidence against (or for) the assumption of discrete processing; nor do they rule out any stage model of the Simon effect or related phenomena. But they do suggest that the additive-factor method may not represent a particularly useful tool in the investigation or understanding of the effects of irrelevant spatial stimulus–response compatibility. Above all, a statistical interaction of any variable with irrelevant spatial correspondence or the lack of it should not be taken as a valid indicator for the location of the Simon and related effects, at least as long as no further theoretical background is provided. According to our hypothesis, the conflict that causes the Simon effect may happen anywhere in the system as long as both the relevant and the irrelevant codes exert any influence on what goes on there. That is, factors affecting quite early processes may interact with the Simon effect, not because these processes take place at the same stage as the correspondence-dependent conflict, but because these factors have an impact on the time-point of formation of the relevant and the irrelevant codes. In other words: processes that take place at one stage may affect processes at another stage without direct interaction.

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