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Spontaneous decay of response-code activation

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Summary. Two experiments investigated whether the Simon effect (i.e., faster responses to spatially corresponding than to noncorresponding stimuli, with stimulus location being irrelevant) is affected by the frequency of noncorrespondence trials. Stimulus discriminability (Experiment 1) and immediate or delayed stimulus formation (Experiment 2) was varied in order to manipulate the temporal relationship between coding of the relevant stimulus information and of stimulus location. As was expected, the Simon effect decreased from high to low discriminability and from immediate- to delayed-stimulus formation. This is consistent with the notion of a gradual decay of location-induced response-code activation. Moreover, the Simon effect decreased with increasing frequency of noncorrespondence trials and was even reversed with higher frequency. This demonstrates strategic preparation of stimulus processing and/or response selection based on irrelevant location information. However, frequency did not modify the interaction between S–R correspondence and stimulus discriminability or stimulus formation, this suggesting that code decay is not a result of a strategy, but an automatic process.

Introduction

Human performance is not immune to the impact of irrelevant stimulus information. This is strikingly demonstrated by the Simon effect (Simon & Rudell, 1967), which occurs when subjects react with spatially defined responses to stimuli with varying (but irrelevant) location. For example, if a stimulus calls for a left-hand response, reaction time is shorter when the stimulus appears on the left-hand than on the right-hand side. That is, irrelevant stimulus information facilitates ipsilateral, and/or interferes with contralateral, responses. It was found that the Simon effect is not so much based on the correspondence between stimulus and hand, but on the spatial relationship between stimulus and effector location or response goal (Guiard, 1983; Hommel, 1993a; Wallace, 1971). This rules out an anatomical explanation and suggests that the critical relationship is that between abstract stimulus codes and response codes (Wallace, 1971, 1972).

There is, in fact, evidence that codes of responses that are performed or aimed at locations ipsilateral to the stimulus are automatically activated by location cues, as was proposed by Simon (1969) or Kornblum, Hasbroucq, and Osman (1990). For instance, the Simon effect can occur long after the response proper has been selected (Hommel, 1994a). In this study, subjects were informed about the correct (left or right) response by a spatially neutral stimulus from trial to trial, but were not allowed to respond immediately. Instead, after 1 s a Go or a No-go signal appeared on the left-hand or on the right-hand side, indicating whether the response should be performed or not. There was a pronounced Simon effect – that is, responses were faster with spatial correspondence between response and Go signal. This again rules out accounts that relate the Simon effect to problems with stimulus identification (Hasbroucq & Guiard, 1991; Stoffels, van der Molen, & Keuss, 1989). Furthermore, measurements of lateralized readiness potentials (Leuthold & Sommer, 1993; Sommer, Leuthold, & Hermanutz, 1993) and of subthreshold motor activities in response fingers (Zachay, 1991), as well as single-cell recordings in the motor cortex of the rhesus monkey (Georgopoulos et al., 1989), revealed that when the stimulus signals a noncorresponding response, the incorrect (but spatially corresponding) response is activated to a certain degree before the correct response is carried out. So there are good reasons for relating the Simon effect to problems with response selection or, more precisely, to location-induced automatic activation of response codes.[1]

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[1] The present study was motivated by a response-related view. However, the particular experimental logic employed here does not depend on whether response-related accounts of the Simon effect are really more convincing than stimulus-related ones (see Hommel, 1994a), nor will the results obtained discriminate between these views. So the sceptical reader may interpret *response code* as *response-related code*, thus leaving a theoretical loop-hole for stimulus-identification approaches

The aim of the present study was to investigate what happens to a response code after its automatic activation. The simplest possibility, that nothing happens and activated codes remain activated, is not very likely, as an infinite accumulation of activity would result in behavioral chaos. It is more plausible to assume some kind of decay of response-code activation (Hommel, 1993b; van der Heijden, 1981) that could also account for the findings of Simon, Acosta, Mewaldt, and Speidel (1976, Experiment 1), as well as of Umiltà and Liotti (1987, Experiments 3 and 4). In the experiment of Simon et al., subjects had to delay responding to the lateralized stimulus until the presentation of a spatially neutral Go signal, which came up 0, 150, 250, or 350 ms after stimulus onset. As it turned out, the size of the Simon effect decreased with increasing Go-signal delay. So, as is consistent with the notion of automatically activated, but fast-decaying, response codes, the cause of the Simon effect fades away after a short time. Umiltà and Liotti (1987) varied relative stimulus position as well as stimulus side and precued one or the other from trial to trial. Although, when not precued, both relative position and side produce a Simon effect (Lamberts, Tavernier, & d'Ydewalle, 1992), Umiltà and Liotti (1987) demonstrated that a precued dimension no longer affects performance. That is, when information as to the side was given beforehand, only relative position yielded a Simon effect, but when relative position was precued, only side produced an effect. This is also consistent with the idea that the impact of spatial information on response-selection processes decreases with time.

The decay notion suggests the following expectation. If the Simon effect results from a response conflict and if one of the conflicting parties (i.e., the response code activated by the location cue) becomes gradually deactivated, then the Simon effect should be the smaller, the later in time the conflict arises – that is, the later the other conflict party shows up. In other words, the Simon effect should be the smaller, the more time is needed to process the relevant stimulus information and to activate the correct response. When this information is processed rapidly, location-induced activation is high and a massive conflict (= Simon effect) results. When it is processed slowly, location-induced activation has time to decay, so that the conflict is weak, or even absent. So every experimental manipulation that slows down the processing of the relevant information without affecting the timepoint of location coding should decrease, or even eliminate, the Simon effect.

There is in fact considerable empirical support for this assumption. In several studies, a variety of factors was found to interact underadditively with correspondence, such as stimulus eccentricity, stimulus quality, and contrast (Hommel, 1993b), memory set size (Hommel, 1994b), as well as stimulus–context similarity (Hommel, 1994c). In addition, McCann and Johnston (1992) found a decreased Simon effect as a result of the insertion of a secondary task. While these findings strongly suggest a decay interpretation, it remains to be clarified how the decay of response-code activity is achieved. There are two obvious options. First, code activation may decay spontaneously, either as a function of time, or because of some automatic self-inhibition (MacKay, 1987). Second, response-code activity may underlie voluntary control. As the actor learns that location-induced response activation is misleading in half of the cases, he or she may strategically inhibit location-related responses. Thus, the question is whether response-code activation decays as a result of automatic or of strategic processes.[2]

An obvious means of finding out whether strategies play a role in a task is to manipulate their utility. In Experiment 1, the frequency of noncorresponding trials was manipulated so that the benefit of a strategy to inhibit location-induced response codes was rather high (75%) or absent (50%). In Experiment 2, more extreme frequencies were compared (80% vs. 20%). If the decay of response-code activation resulted from a strategy, one would expect the decay to be more pronounced with higher, than with lower, frequencies of noncorrespondence trials. If, on the contrary, codes automatically decayed over time, no effect of frequency should occur. There are, however, two reasons for doubting whether a modification of the Simon effect by frequency or the lack of it as such is sufficiently diagnostic.

The first difficulty in interpreting frequency effects has to do with processing speed. The idea that response codes are automatically activated by location cues before the relevant stimulus information is processed presupposes that location can be processed independently of, and earlier than, identity information. If this is true, location may be used as a stimulus and/or a response cue that is uninformative only with 50% noncorrespondence trials, but informative in every other case. With lower frequencies, it would be a useful strategy to anticipate the stimulus and/or to prepare the response[3] that corresponds to the location cue, but the noncorresponding stimulus and/or response with frequencies above 50%. Such a preparation strategy would produce an increase in the Simon effect with low frequencies and a decrease, or even a reversal, with high frequencies. Unfortunately, this result pattern is very similar to the underadditive interaction of correspondence and frequency discussed above as a possible indicator of strategic response-code inhibition.

With a Stroop design, evidence for stimulus–response preparation by utilization of information from irrelevant stimulus attributes has in fact been repeatedly obtained (Logan, 1980; Logan & Zbrodoff, 1979, 1982). In these studies, the size of the Stroop effect varied as a direct negative function of the frequency of conflict trials. While, logically, this may have been produced by preparation as well as by inhibition, the latter possibility conflicts with results of Logan, Zbrodoff, and Williamson (1984). Their subjects were able to utilize the frequency of conflict trials

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[2] In the following, automatic and voluntary *de*crease of stimulus- or response-code activation will be distinguished as *spontaneous decay* or *strategic inhibition*, respectively. In contrast, automatic and voluntary *in*crease of activation will be referred to as (e.g., stimulus-induced) *automatic activation* or *preparation* (of stimulus identification or response selection), respectively

[3] With a one-to-one mapping of stimuli and responses, stimulus-related preparation (anticipation) cannot be distinguished from response-related preparation (preselection). Therefore, the term *preparation* will be used here in the most general sense to encompass both

as long as there were only two response alternatives, but not when these increased from two to four. This would be hard to understand if frequency effects were due to strategic inhibition, because the expenditure of inhibiting an activated code should not depend on the number of alternative codes. Stimulus – response preparation, on the other hand, is more difficult with a larger response set, because the number of rules defining which response has to be activated as a function of which distractor grows with the number of response alternatives. Thus, the decrease of the Stroop effect with the increasing frequency of conflict trials is most likely produced by preparation, rather than inhibition. Analogously, a modification of the Simon effect by frequency may indicate the utilization of frequency information for stimulus – response preparation, rather than response inhibition.

The second problem for an interpretation of frequency effects is that decay happens over time. For this reason, a possible null effect of frequency may simply reflect insufficient time for inhibiting the response code actively, rather than indicating automatic decay. Therefore, we have to choose experimental conditions that would actually permit response-code decay. In order to do this, the "speed-factor" logic suggested elsewhere (Hommel, 1993 b) was applied in the present study. Factors were introduced that are likely to influence the speed of processing the relevant information without affecting the availability of location information. An easier level of these speed variables should guarantee high-speed processing, so that the response conflict arises after a short time, involving a strong location-induced code. A more difficult level slows down the processing of the relevant information, so that the location-induced code has time to decay. If so, the Simon effect is smaller under the difficult factor level than under the easier one, indicating code decay in each frequency condition. If decay were due to strategic factors, the decrease of the Simon effect from the easy to the difficult level would be more pronounced the higher the frequency of noncorrespondence trials is. If decay were automatic, the decrease would be the same in all frequency conditions.

The introduction of factors that selectively affect the speed of processing the relevant stimulus information not only makes it easier to interpret null effects of frequency, it also provides a means of distinguishing between strategic response-inhibition and preparation effects. As has been pointed out, a general influence of the frequency of noncorrespondence trials on the Simon effect is not diagnostic for strategic response inhibition, whereas an enhanced frequency effect from an easy to a difficult level of a speed factor would well be. On the one hand, we cannot exclude the possibility that preparation also becomes more effective with difficult, than with easier, levels of the speed variable. Preparation processes may need some time, so that with longer stimulus processing, preparation time increases too. On the other hand, preparation and inhibition would yield slightly different result patterns over time, that is, with increasingly difficult levels of the speed variable. If preparation becomes stronger over time, the Simon effect would increase over speed factor levels with frequencies under 50%, but decrease (or reverse) with frequencies exceeding 50%. In contrast, response inhibition would always decrease (or reverse) the Simon effect, to a degree that varies as a function of frequency.

To summarize, the following experiments varied speed variables together with the frequency of noncorrespondence trials. Preparation would be indicated by a weakening influence of frequency on the size of the Simon effect, that is, by an underadditive interaction of correspondence with frequency. Spontaneous decay of response codes would be indicated by a decrease in the Simon effect with rising difficulty of the speed-factor level, that is, by an underadditive interaction of correspondence with the speed factor. Decay produced by strategic inhibition, on the contrary, would manifest itself in a dependency of this decrease over levels on frequency, that is, in a higher-order interaction of correspondence, speed factor, and frequency.

Experiment 1

In Experiment 1, the frequency of noncorrespondence trials was 50% or 75%, in different groups, and stimulus discriminability was employed as the speed factor. It was expected that, first, high discriminability yields faster responses than low discriminability. Second, preparation effects may produce a decrease in correspondence or Simon effects from the 50% to the 75% condition. Third, spontaneous decay of response-code activation would be indicated by a reduction of the correspondence effect from high to low discriminability. On the contrary, strategic inhibition (or, with a slightly different pattern, preparation) would be indicated by a modification of the relationship between correspondence and discriminability by frequency.

Method

Subjects. Forty-four adults, 21 female and 23 male, were paid to participate in single sessions of about 25 min. They reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment.

Apparatus and stimuli. Stimulus presentation and data acquisition was controlled by a Hewlett Packard Vectra QS20 computer, interfaced with an Eizo MD-B11 graphics adaptor and attached to an Eizo 9070s or 9080i monitor. Responses were given by pressure on the left or right shift key of the computer keyboard with the corresponding index finger. The fixation point was a white asterisk and the stimuli were red and blue rectangles, presented on a black background. Stimulus colors were manipulated by setting the green-register of the graphics card to zero, and the red- and blue-register to dissimilar (30 vs. 0 from 63), or to similar (30 vs. 25) values, depending on the discriminability condition. The results were clear-red (2.5 cd/m^2) versus clear-blue (0.7 cd/m^2) stimuli under high stimulus discriminability and reddish (2.8 cd/m^2) versus bluish (2.2 cd/m^2) lilac tones under low discriminability. From a viewing distance of approximately 60 cm, the stimuli measured 0.6° in width and 1.2° in height. The fixation point appeared at the geometrical center of the screen, and the stimuli were centered 1° to its left or right. The mapping of responses to stimuli was constant over subjects (red = left response, blue = right response).

Design and procedure. Frequency of noncorrespondence trials was a between-groups variable, being 50% for one and 75% for another group of 22. All other variables varied within subjects. Each subject was required to perform in the two blocked conditions of stimulus discriminability (high vs. low), in balanced order. In each discrimin-

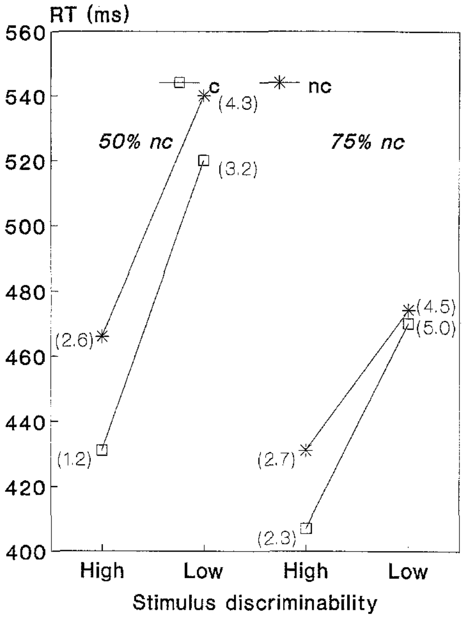

Fig. 1. Mean reaction times and error percentages (in parentheses) in Experiment 1 as a function of high vs. low stimulus discriminability, spatial S–R correspondence (c) vs. noncorrespondence (nc), and percentage of noncorrespondence (nc) trials

ability condition, subjects worked through two practice and 20 experimental eight-trial blocks. In the 50% group, each of these blocks comprised two replications of each of the four possible combinations of two stimuli and two stimulus locations, in random order. In the 75% group, each block comprised one trial of each correspondence condition and three replications of each noncorrespondence condition.

In each trial, the sequence of events was as follows. After an intertrial interval of 1,500 ms, the fixation point was presented for 500 ms, followed by a blank interval of 1,000 ms. Subsequently, the stimulus appeared for 150 ms. The program waited until the response was given, but no longer than 1 000 ms. Responses with the wrong key were counted as errors and responses with latencies above 1,000 ms were considered to be missing. In both cases, auditive error feedback was given, while the trial was recorded and then repeated at some random position in the remainder of the block.

Results

Missing trials (<1%) were excluded from analyses. Per subject, median reaction times (RTs) and proportions of errors (PEs) were computed as a function of stimulus discriminability (high vs. low), stimulus location (left vs. right), and response location (left vs. right). The four-way analyses of variance (ANOVAs) of the RT and PE data comprised one between-subjects factor (frequency of noncorrespondence trials) and three within-subjects factors (discriminability, stimulus location, response location).

The RT analysis revealed three main effects. Responses were faster in the 75% condition than in the 50% condition (446 vs. 490 ms), $F(1,42) = 6.56$, $p < .05$; high discriminability produced faster responses than low discriminability (434 vs. 501 ms), $F(1,42) = 85.32$, $p < .001$; and right stimuli were responded to slightly faster than left stimuli (465 vs. 470 ms), $F(1,42) = 6.80$, $p < .05$. Further, six interaction effects were significant, or nearly so. First, as Figure 1 shows, the discriminability effect tended to be somewhat smaller in the 75% group than in the 50% group, $F(1,42) = 3.80$, $p < .06$. Second, right-hand responses were faster than left-hand responses in the 50% group (487 vs. 492 ms), while the reverse was true for the 75% group (450 vs. 441 ms), $F(1,42) = 4.61$, $p < .05$. (Note that, with 21 right-handers in either group, this cannot be associated with handedness.) Third, in the 50% group, right stimuli yielded faster responses than left stimuli under high (445 vs. 452 ms), but not under low, discriminability (530 vs. 531 ms), while in the 75% group the right stimulus advantage was present under low (467 vs. 477 ms), but not under high, discriminability (419 vs. 419 ms), this producing a Frequency × Discriminability × Stimulus Location interaction, $F(1,42) = 4.19$, $p < .05$. There is no apparent explanation for this interaction, and it was not replicated in similar experiments.

The last three interactions were more important: There was a clear Stimulus Location × Response Location interaction, $F(1,42) = 68.85$, $p < .001$, confirming that left responses were faster to left than to right stimuli (458 vs. 474 ms), while right responses were faster to right than to left stimuli (456 vs. 482 ms). This correspondence, or Simon effect, was modified by two three-way interactions (see Figure 1). An interaction of Stimulus Location × Response Location × Frequency, $F(1,42) = 7.50$, $p < .01$, indicated that the correspondence effect was twice as large in the 50% condition as in the 75% condition (28 vs. 14 ms). An interaction of Stimulus Location × Response Location × Discriminability, $F(1,42) = 12.43$, $p < .001$, showed that the correspondence effect was more than twice as large under high, than under low, stimulus discriminability (29 vs. 12 ms). This effect was not modified by frequency ($p > .5$). The only significant effect in the ANOVA of the error data was that errors were more frequent under low than under high discriminability (4.2% vs. 2.2%), $F(1.42) = 24.23$, $p < .001$.

Discussion

The results replicate earlier findings and, in addition, allow a first conclusion on the automatic-strategic issue under discussion. First, the main effect of the speed factor, stimulus discriminability, indicates that the preconditions for a different amount of response-code decay in the two discriminability conditions were fulfilled. While, under high discriminability, the time delay between processing stimulus location and stimulus color should have been rather small, a larger delay is to be expected under low discriminability. That is, the location-induced response code had considerably more time to decay under low, than under high, stimulus discriminability.

Second, the correspondence or Simon effect is smaller under low, than under high, stimulus discriminability. This is consistent with the frequent finding that correspondence effects decrease from easier to more difficult levels of speed factors and can be explained by response-activation decay along the lines of Hommel (1993b).

Third, the correspondence effect decreases with higher frequency of noncorresponding trials. This is clear evidence for a stimulus–response preparation effect, already demonstrated in a Stroop design by Logan and Zbrodoff (1979). Obviously, subjects use location information to facilitate stimulus indentification and/or to prepare the noncorresponding response. Though the perfect correlation of stimuli and correct responses in this experiment does not permit a decision as to whether preparation referred to stimulus or response processing, there are some clues that favor a stimulus-related view. As is shown in Figure 1 and indicated by the marginally significant interaction of group and discriminability, the 75% group did much better than the 50% group under low discriminability, while the difference was less pronounced under high discriminability. In other words, performance tended to be less hampered by low discriminability in the 75% group than in the 50% group. This may suggest that the 75% group was able to reduce the difficulty to distinguish the less-discriminable stimuli by using frequency information. However, while similar result patterns have shown up in as yet unpublished experiments of the author with other speed factors, there were no such frequency-related effects in Experiment 2. So a decision between stimulus and response preparation as well as the explanation of the frequency main effect certainly requires further investigation.

Fourth, and this is the most important finding, the interaction of correspondence and discriminability is not modified by frequency. As Figure 1 shows, the correspondence effect is reduced from high to low discriminability, but the amount of reduction is nearly the same in both frequency conditions. If strategic response inhibition were involved, it should be applied with greater probability under a higher than under a lower rate of noncorresponding trials. This would lead to a stronger decrease in correspondence effects over discriminability levels under higher rates. As this is not the case, the results suggest an interpretation in terms of automatic decay of response codes.

Experiment 2

The results of Experiment 2 support the idea of a spontaneous decay of response-code activation. However, the validity of this conclusion depends on the speed-factor logic proposed above. That is, the two levels of stimulus discriminability in Experiment 1 were assumed to produce two differently pronounced delays in the processing of the relevant information in relation to the processing of stimulus location. The greater delay at the difficult factor level should provide more time to inhibit the response code actively than the smaller delay at the easier level, and this time should be utilized better with high than with low frequency of noncorrespondence trials.

Experiment 2 was conducted to test whether this rather indirect logic really holds. In order to do this, the temporal distance between relevant and irrelevant information was manipulated directly by presentation of location information either together with the relevant stimulus information (the immediate condition) or some time earlier (the delay condition). This was achieved by presenting either at once or gradually the screen pixels that made up the stimulus letter, so that location information was available with the first pixels, but identity information (provided by discriminative pixels) was or was not held back for some time (cf. Hommel, 1993 b, Experiment 5). The immediate condition should work exactly as assumed for the easy levels of speed factors: the relevant information is processed early and encounters a location-induced response code that is still active, which results in a strong conflict. The delay condition, on the other hand, should work like a difficult speed-factor level – that is, the relevant information is processed late, so that a conflicting location-induced response code has time to decay.

A further aim of Experiment 2 was to include more extreme frequencies of noncorrespondence trials. In Experiment 1, frequency had had the effect of merely diminishing the size of the correspondence effect. This was attributed to stimulus–response preparation by utilization of spatial stimulus information. However, the results of Logan and colleagues (Logan, 1980; Logan & Zbrodoff, 1979, 1982) suggest that it may be possible even to reverse the correspondence effect by the inclusion of frequencies that are considerably smaller than 50%. Consequently, Experiment 2 employed two frequencies repeatedly demonstrated by Logan et al. to produce an inversion of Stroop-like effects, namely 20% and 80%.

Method

Subjects. Twenty adults, 12 female and 8 male, were paid to participate in two sessions of about 35 min each. They reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment.

Apparatus and stimuli. The experiment and data acquisition were controlled by a Rhotron VME system, connected to an Atari SM124 monochrome monitor (640×400 pixel). Responses were made by pressure of 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 3°-wide and 1.38°-high white field. The central 0.3°×0.2° fixation cross and the stimuli were black. The stimuli were the uppercase letters U and D, subtending 0.2°×0.4° in space and appearing 0.6° to the left or right of the center. In the immediate-formation condition, the whole stimulus appeared on the screen at once. In the delayed-formation condition, however, the stimulus built up gradually within 196 ms (3–4 pixel per 14-ms refresh cycle). Before completion, no letter-identity information was available, that is, a U was not discriminable from a D during the formation period (for further details, see Hommel, 1993 b, Experiment 5).

Design and procedure. All variables varied within subjects. The frequency of noncorrespondence trials was 20% in one and 80% in the other session, in balanced order. The remaining design was analog to that in Experiment 1. Within each session, the subject was required to perform under the two blocked stimulus-formation conditions (immediate vs. delayed), in balanced order. In each formation condition, subjects worked through 2 practice and 20 experimental eight-trial blocks. In the 20% session, each of these blocks comprised four replications of each correspondence condition and one replication of each noncorrespondence condition, while, in the 80% session, a block comprised one replication of each correspondence condition and four replications of each noncorrespondence condition.

The procedure was as in Experiment 1, except that in the immediate condition, the stimulus appeared at once, while in the delayed condition it built up gradually within 196 ms. The stimulus stayed on until the end of the trial. Reaction time was defined as the

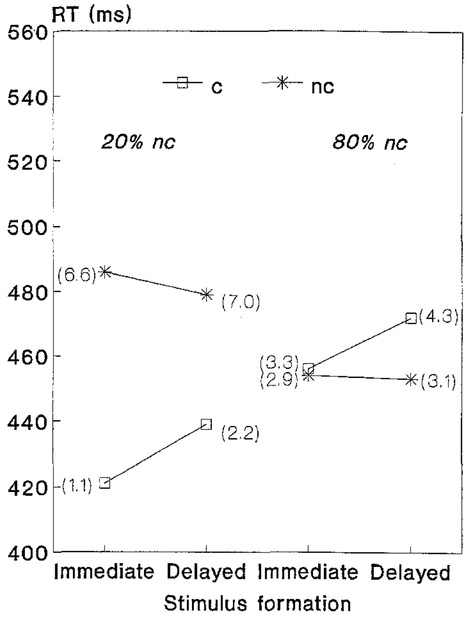

Fig. 2. Mean reaction times and error percentages (in parentheses) in Experiment 2 as a function of immediate vs. delayed stimulus formation, spatial S–R correspondence (c) vs. noncorrespondence (nc), and percentage of noncorrespondence (nc) trials

time elapsing between presentation of the distinctive stimulus pixels (i. e., letter-identity information) and the key press.

Results

Missing trials (<1%) were excluded from analysis. The remaining data were treated as in Experiment 1, except that stimulus formation (immediate vs. delayed) replaced the discriminability factor, and frequency of noncorrespondence trials (20% vs. 80%) was treated as a within-subjects factor.

An ANOVA of the RTs produced four effects. First, a Stimulus Location × Response Location effect, $F(1,19) = 18.75$, $p < .001$, showed that left responses were faster to left than to right stimuli (452 vs. 468 ms), while right responses were faster to right than to left stimuli (442 vs. 468 ms). Second, this correspondence effect was modified by an interaction of Stimulus Location × Response Location × Frequency, $F(1,19) = 33.17$, $p < .001$. As Figure 2 shows, correspondence yielded 52-ms faster responses than noncorrespondence in the 20% condition, but 11-ms slower responses than noncorrespondence in the 80% condition. Third, an interaction of Stimulus Location × Response Location × Stimulus Formation, $F(1,19) = 9.12$, $p < .005$, showed that the correspondence effect was about three times as large with immediate- than with delayed-stimulus formation (31 vs. 11 ms). This effect was not modified by frequency ($p > .5$). Finally, there was an interaction of Response Location × Frequency × Stimulus Formation, $F(1,19) = 4.47$, $p < .05$, indicating that in the 20% condition the advantage of the right over the left hand was more pronounced under immediate (448 vs. 456 ms) than under delayed formation (457 vs. 460 ms), while in the 80% condition the right-hand advantage was more pronounced under delayed (460 vs. 465 ms) than under immediate formation (454 vs. 456 ms). There is no apparent explanation for this interaction, and it was not replicated in similar experiments.

An ANOVA of the PE data yielded a significant Stimulus Location × Response Location effect, $F(1,19) = 5.62$, $p < .05$, confirming that correspondence produced fewer errors than noncorrespondence in left (2.7% vs. 4.4%) and right responses (2.7% vs. 5.4%). This correspondence effect was modified by an interaction of Stimulus Location × Response Location × Frequency, $F(1,19) = 12.19$, $p < .005$. This was due to the fact that fewer errors were made under correspondence than under noncorrespondence in the 20% condition, but not in the 80% condition, where this relationship was slightly reversed (see Figure 2).

Discussion

The results are in full accordance with those of Experiment 1. Stimulus formation had an effect on correspondence analogous to that of stimulus discriminability in decreasing correspondence effects from the immediate to the delay condition. This is further evidence for the idea that variables affecting processes that precede response selection mainly function as speed factors, determining the temporal relationship between response-code activation by relevant and by irrelevant information, thus determining the degree of code conflict (Hommel, 1993 b). Figure 2 shows that, as in Experiment 1, the decrease in correspondence effects is the same in both frequency conditions. That is, there was again no indication of strategic-response inhibition, although the frequency manipulation was considerably higher in this experiment than in Experiment 1.

A further result of interest is the reversal of the correspondence effect in both RT and PE data under 80% noncorrespondence trials. This replicates the results of Logan and colleagues (Logan, 1980; Logan & Zbrodoff, 1979, 1982), although they used a Stroop-like task in which the words ABOVE and BELOW appeared above or below a fixation point and were responded to by pressure of a left or a right button. In opposition to the Simon tasks of the present study, such a task does not contain spatial correspondence or noncorrespondence between a stimulus attribute and a response attribute. This suggests that the frequency effect is rather general and may occur in every task that includes informative stimulus attributes that can be processed earlier or faster than the reaction-stimulus attribute proper. The importance of the latter constraint became apparent in the study of Logan and Zbrodoff (1979, Experiment 1). When words were responded to, the frequency of conflicting locations had a large effect, but when location was responded to, there was no effect of word compatibility or of the frequency of conflicting words. This is to be expected, because, as is confirmed by a main effect of about 100 ms, spatial information was processed earlier or faster than word information, so that at the time of location-based responses word information was not processed sufficiently to guide stimulus–response preparation.

General discussion

Two experiments were conducted to investigate whether response-code decay – as indicated by a decrease in correspondence or Simon effects with the temporal delay of relevant stimulus information to stimulus location – results from a spontaneous decrease of activation over time, or rather from strategic response-code inhibition. The general logic was to manipulate the utility of an inhibition strategy by variation of the frequency of correspondence between stimulus location and response location. With lower frequencies, location information would activate the correct response more often than the incorrect one, so that strategic inhibition would not be useful, whereas with increasing frequency inhibition would become a more and more sensible strategy. In order to vary the time provided for inhibition to unfold, the temporal distance between the processing of location information and the processing of the relevant stimulus attribute was manipulated by the use of high and low stimulus discriminability and immediate and delayed stimulus formation.

Although the two experiments employed different variables to manipulate the temporal relationship between location and identity information, the results were very much the same. First, correspondence effects decreased from high to low discriminability and from immediate to delayed stimulus formation. This is consistent with the findings of Hommel (1993 b, 1994 b, 1994 c) and of McCann and Johnston (1992) and can be interpreted as showing decay of location-induced response-code activation over time (Hommel, 1993 b).

Second, correspondence effects were also reduced, and even reversed, with increasing frequency of noncorrespondence trials. This is strong evidence for the generality of the finding of Logan and Zbrodoff (1979), that irrelevant, but informative, stimulus attributes can be used to facilitate identification of, and/or responding to, the relevant stimulus information, at least when the former is available earlier, or processed more rapidly, than the latter. Furthermore, it supports the idea of Logan and Zbrodoff (1979) that performance in conflict tasks, such as the Stroop or Simon tasks, may be a combination of both automatic processes as well as strategies.

Third, there was not even a hint of a modification of the decay rate by frequency, which is strong evidence against an interpretation of decay effects in terms of strategical factors. As it seems, response codes activated by location information decay at a fixed rate that does not depend on the utility of the activation. However, the effect of automatic decay can be compensated, or even overcompensated, by strategical stimulus–response preparation, as the frequency effects on correspondence clearly demonstrate. That is, automatic decay yields rather small effects compared with the impact of voluntary (or at least highly adaptive) preparation.

Finally, it should be emphasized that the present findings concern the issue of whether response-code decay is automatic or the result of a strategy, but not whether inhibition mechanisms as such are or are not involved in solving response conflicts. Although *strategic* inhibition of response codes does not seem to be the cause of the activation decay in the Simon task, there is no reason to deny the existence of inhibitory interactions between stimulus or response codes at all. On the contrary, evidence for inhibitory processes has been gathered from a wide range of tasks (e. g., Gernsbacher & Faust, 1991; Lowe, 1985; Neill, 1977; Tipper, 1992; Yee, 1991), and the very concept of a response conflict in explaining correspondence effects necessarily comprises the idea of an inhibitory relationship between alternative responses or their codes. So activation of one response implies inhibition of another. Further, the finding that response-code decay is spontaneous in no way excludes that it is caused by, say, automatic self-inhibition (MacKay, 1987) or some other inhibitory process. However, all this does not touch the main conclusion from the present experiments: that the loss of activation of response codes that were activated by irrelevant location cues does not depend on the utility of this loss and, consequently, cannot be attributed to a strategy of inhibiting response tendencies.

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