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Perceptual and attentional factors in encoding irrelevant spatial information

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Abstract Numerous studies found superior performance when the irrelevant location of a stimulus and response location were corresponding than when they were not corresponding (Simon effect), suggesting that stimulus location is processed in an obligatory manner. The present study compared Simon effects from the location of a relevant (i.e., to-be-attended) object to those from the location of an irrelevant (i.e., to-be-ignored) object. In four experiments, participants were presented with a rectangular frame and a square, with the relevant object in green or red color and the irrelevant object in gray or white color. Participants' task was to respond with a lateral keypress to the color of the relevant object, and we varied spatial correspondence between the location of the relevant or the irrelevant object and the response, respectively. Results consistently showed larger Simon effects from the location of the relevant than from the irrelevant object, even when the irrelevant object was made very salient. These results suggest that location processing is largely confined to relevant (i.e., attended) objects, stressing the role of attention shifts for location encoding.

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Introduction

Many everyday observations suggest a limitation in our ability to ignore irrelevant information. When trying to read a newspaper on the bus, for example, the controversy of a couple sitting next to you is very distracting. Similarly, several observation from the psychological laboratory suggest that people process irrelevant information along with the relevant information, despite having been instructed to ignore the irrelevant information. For example, in the Simon task, participants process irrelevant stimulus location despite knowing that it is irrelevant for the task at hand. The present study investigates the reasons for why in this task people process irrelevant location information. In particular, it investigates whether irrelevant location information is only processed when it belongs to the same perceptual object (or perceptual group) as the relevant information.

The mechanisms of selective attention, that is, the ability to limit processing to relevant information and to ignore irrelevant information, are often studied in filtering (or congruency) tasks (Kahneman & Treisman, 1984). The basic method is to instruct participants to respond to a relevant stimulus and to manipulate the congruency (or correspondence) either between the relevant stimulus and an irrelevant stimulus [stimulus–stimulus (S–S) correspondence] or between an irrelevant stimulus and the response [stimulus–response (S–R) correspondence]. The observation of congruency or correspondence effects suggests that participants have processed the irrelevant stimulus.

The most widely used congruency tasks are the Eriksen flanker task, the Stroop task, and the Simon task. In the Eriksen flanker task, the experimenter manipulates S–R correspondence between irrelevant flanker stimuli and the response to a central target item. For example, when participants are required to press a left key to the target letters 'A' and 'B', and a right key to the target letters 'C' and 'D', faster responses with corresponding conditions (e.g., ABA) than with noncorresponding conditions (e.g., DAD) demonstrate that participants processed the flanker stimuli up to the level of response selection (Eriksen, 1995, for a review). In the classic Stroop task (Stroop, 1935), participants have to name the ink color of a color word. The typical observation is that color naming is much faster for congruent items (e.g., the word 'red' printed in red ink color) than for incongruent items (e.g., the word 'red' printed in blue ink color). The Stroop effect demonstrates that the meaning of a word is often processed, even when it is irrelevant for the task at hand, and participants are instructed to ignore it (MacLeod, 2005, for a review). Finally, in the Simon task, the experimenter manipulates spatial S–R correspondence between the irrelevant location of a stimulus and the location of a response to a nonspatial stimulus feature. For example, participants may be required to press a left key to a green stimulus, and to press a right key to a red stimulus. The term Simon effect denotes the finding of faster responses to spatially corresponding stimuli (e.g., the green stimulus appearing at a left location) than to spatially noncorresponding stimuli (e.g., the green stimulus appearing at a right location). The effect demonstrates that the irrelevant location of a stimulus is processed although it is irrelevant for the task at hand, and participants are usually told to ignore it.

The effects of irrelevant information on performance are often attributed to automatic processing of the respective stimulus feature. For example, popular accounts propose two consecutive steps of automatic processing to explain the Simon effect. In a first step, the cognitive system automatically encodes the irrelevant location of the stimulus, and forms a spatial stimulus code. In a second step, the spatial stimulus code automatically activates a spatially corresponding response code (e.g., Hommel, 1997; Kornblum, Hasbroucq, & Osman, 1990; Zorzi & Umiltà, 1995). Two mechanisms of spatial stimulus code formation have been proposed. The first mechanism involves a shift of spatial attention. In the usual Simon task, the onset of the imperative stimulus might trigger a shift of spatial attention from central fixation to the location of the imperative stimulus, and the direction of this attention shift might produce a spatial stimulus code (Nicoletti & Umiltà, 1994; see Stoffer & Umiltà, 1997, for a review). Alternatively, the location of the imperative stimulus might also be encoded with regard to a salient reference object (e.g., the fixation point; referential-coding account, Hommel, 1993a).

Previous studies suggest that the processing of irrelevant stimuli in the Eriksen task, and the processing of irrelevant word meaning in the Stroop task is not strongly automatic, but depends upon whether the irrelevant stimulus belongs to the same perceptual object (or group) as the relevant stimulus. For example, Kramer and Jacobson (1991) demonstrated that flankers had much larger effects in the Eriksen task when they had the same color as the target than when they had a different color. Similarly, Wühr and Waszak (2003) showed that irrelevant color words had much larger effects in the Stroop task when the words were part of the relevant object, the color of which had to be named, than when the words were part of an irrelevant object. In other words, information that belongs to a relevant object, or that it is similar to the relevant object, is more likely to be processed than information that belongs to an irrelevant object or group.

It is less clear how belonging to the same object or to different objects affects the processing of irrelevant location information. Results from the so-called accessory-stimulus version of the Simon task appear to suggest that the processing of irrelevant location information is highly automatic. In this version of the Simon task, the location of a laterally presented tone affects spatial responses to a centrally presented visual stimulus (e.g., Simon & Craft, 1970). In order to explain Simon effects in the accessory-stimulus version of the Simon task, proponents of the attention-shift hypothesis might propose that the onset of a tone triggers a shift of visual or auditory attention to the location of the tone, which produces a spatial stimulus code that affects the selection of a spatial response to the visual stimulus. Alternatively, however, Simon effects in the accessory-stimulus version of the Simon task may result from the fact that the tone and the visual stimulus, which are presented simultaneously, are perceptually grouped together and perceived as a single object, which may affect the localization of the visual stimulus. Research on the so-called 'ventriloquism effect' demonstrates that participants mislocalize a visual stimulus in the direction of a tone presented simultaneously with the visual stimulus (e.g., Bertelson, Vroomen, & de Gelder, 2000; see, Bertelson, 1999, for a review). If ventriloquism plays a role in the accessory-stimulus version of the Simon task, correspondence effects in this task are not due to the automatic and independent localization of relevant and irrelevant stimuli, but to the effect of an irrelevant tone on localizing a relevant visual stimulus.

Interestingly, the two theories of spatial stimulus code formation appear to predict differences in the capacity for encoding the location of several visual stimuli. In particular, with regard to the attention-shift account, most researchers agree that attention can only attend to one location at a time (e.g., Cave & Bichot, 1999; Posner, 1980; but see Castiello & Umiltà, 1992). Because in most situations attention should rather shift to the relevant stimulus than to an irrelevant stimulus, the attention-shift account predicts a higher probability to observe Simon effects from the location of the relevant stimulus than from the location of an irrelevant stimulus. The referential-coding account does not necessarily make the same prediction. On to this account, it should be possible to encode the location of a relevant object and the location of an irrelevant object simultaneously with regard to a common point of reference (i.e., the focus of attention). Moreover, it is also possible that both mechanisms work in parallel. In this case, both attention shifts and referential coding might encode the location of a relevant object, whereas only the referential-coding mechanism might encode the location of irrelevant objects while attention is focused on a relevant object.

The present study investigates the role of presenting the relevant nonspatial stimulus and the irrelevant spatial stimulus as features of the same object or as parts of the same perceptual group for the processing of the irrelevant location information. The purpose of this investigation was twofold. First, comparing the effects of encoding the location of a relevant object to the effects of encoding the location of an irrelevant object is informative with regard to the automaticity of location or position coding. If encoding the position of stimuli in the visual field was strongly automatic, the location of a relevant stimulus and the location of an irrelevant stimulus should be encoded and affect performance, that is, produce Simon effects. If, however, encoding the position of stimuli in the visual field was not (strongly) automatic, the location of a relevant (i.e., attended) visual stimulus should produce larger correspondence effects than the location of an irrelevant visual stimulus. The second, and related, purpose of the present study was to further investigate the two possible mechanisms for encoding stimulus position in the Simon task.

In each experiment of the present study participants were presented with two stimuli, a rectangle (i.e., frame) and a square (Fig. 1). In Experiments 1 and 2, the frame was always presented at screen center, while the location of the square varied horizontally. Either the frame or the square was presented in green or red color; the other stimulus was gray (Experiment 1) or white (Experiment 2). Participants' task was to press a left or right key in response to the green or red color of the relevant object. The question was whether the location of a relevant square and the location of an irrelevant square produce similar S–R correspondence effects or not. In Experiment 3, the square was always presented at screen center and the location of the frame, which always included the square, varied horizontally. This variation allowed evaluating predictions of the attention-shift and the referential-coding account. In Experiment 4, the irrelevant object temporarily preceded or followed the relevant object in order to assess the time course of processing irrelevant location information.

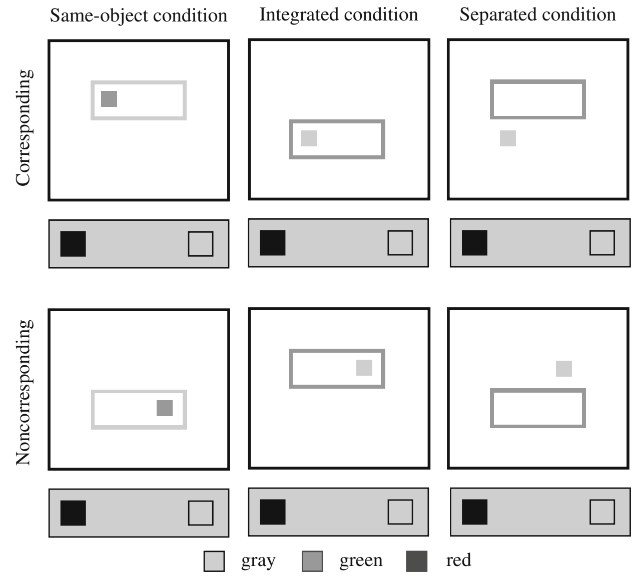

Fig. 1 Example of a stimulus–response configuration for each of the six experimental conditions in Experiment 1. The S–R mapping depicted in the present example is *green-left* and *red-right*. For simplicity, only responses to *green stimuli* are depicted. S–R correspondence refers to the relationship between the irrelevant location of the colored stimulus (i.e., the square in the same-object condition; the frame in the remaining conditions) and the location of the keypress response. A *black key* indicates the correct response key

Experiment 1

Experiment 1 investigated whether the irrelevant location of a relevant object has larger effects on performance than the irrelevant location of an irrelevant object. In particular, we tested whether the location of a relevant object produces larger or similar Simon effects than the location of an irrelevant object.

There were three stimulus conditions in Experiment 1. In the same-object condition, participants responded to a colored square, which appeared inside a frame at a left or right location (Fig. 1, left column). In this condition, the relevant color stimulus and the irrelevant location stimulus were features of the same object. In the integrated-objects condition, participants responded to a colored frame, which contained a gray square at a left or at a right location (Fig. 1, central column). In this condition, the relevant color stimulus and the irrelevant location stimulus were features of the same group of objects. Finally, in the separated-objects condition, participants again responded to a colored frame, and a gray square appeared above or below the frame at a left or right location (Fig. 1, right column). In this condition, the relevant color stimulus and the irrelevant location stimulus were features of different, though adjacent, objects.

The main question was whether the location of the square would produce similar or different Simon effects in the three conditions. Observing similar Simon effects would suggest that encoding the location of visual objects was highly automatic, without being much affected by task relevance. With regard to mechanisms, observing large Simon effects in the conditions with the frame as the relevant object would suggest that referential coding encoded the location of the irrelevant square because we can assume that spatial attention is preferentially directed onto the relevant frame. In contrast, observing larger Simon effects in the same-object condition than in the other conditions would suggest that task relevance modulates the encoding of object location. With regard to mechanisms, asymmetric effects might suggest that one mechanism preferentially encodes the location of the relevant object. Alternatively, asymmetric effects might also result from two mechanisms (i.e., attention shifts and referential coding) encoding the location of the relevant object, whereas only one mechanism (i.e., referential coding) locates the irrelevant object.

Method

Participants

Twenty-one volunteers (17 women) with a mean age of 22 years (range from 17 to 36 years) participated for payment (5 Euro) or course credit. Most of the participants in this and the following experiments were students at the Friedrich-Alexander Universität Erlangen, were naïve with respect to the purpose of the study and classified themselves as having normal (or corrected-to-normal) visual acuity.

Apparatus and stimuli

The experiment took place in a dimly lit room. Participants sat in front of a 17-inch color monitor, which was placed on table, with unconstrained viewing distance of approximately 50 cm. A computer program, written with the ERTS software package (BeriSoft Inc., Frankfurt/Main) and implemented on an IBM-compatible computer, controlled the presentation of stimuli and the registration of responses. Participants responded by pressing the left or right control key on a standard computer keyboard with the left or right index finger, respectively.

The fixation point was a small '+', and it was always presented at screen center. The stimulus display consisted of an unfilled rectangle (frame) and a filled square. The frame measured 8.0° of width and 2.8° of height. The square measured 1.0° by 1.0° of visual angle. Either the frame or the square appeared in red or green color; the other stimulus appeared in gray. The two colors and the gray value were matched in luminance; the average luminance of the stimuli was 11 cd/m² (gray = 11 cd/m², green = 10 cd/m², red = 12 cd/m²). The participants' task was to respond to the colored stimulus by pressing the left key to one color and the right key to the other color. The frame appeared either above or below the horizontal meridian of the computer screen, that is, either the lower or upper side of the frame was presented on the horizontal meridian of the screen. The square appeared either inside or outside the frame (i.e., either on the same or on the opposite side of the horizontal meridian as the frame), and it appeared either to the left or to the right of the vertical meridian of the computer screen. At each location, the distance between the inner edge of the square and the vertical meridian of the screen was approximately 2.3°.

There were three basic stimulus configurations. First, a green or red square appeared inside the gray frame, which was randomly presented above or below the horizontal meridian (Fig. 1, left column). This was the same-object condition in which relevant color and irrelevant location information were bound to the same object (i.e., the square) Second, a gray square appeared inside the green or red frame, which was presented above or below the horizontal meridian (Fig. 1, central column). This was the integrated-objects condition because the stimulus that carried the relevant color information contained the stimulus that carried the irrelevant location information. Finally, a gray square appeared outside the green or red frame, at opposite sides of the horizontal meridian (Fig. 1, right column). This was the separate-objects condition because the relevant color information and the irrelevant location information were conveyed by different objects at different locations. All visual stimuli were presented on a black background.

Procedure

At the beginning of the experiment, the instructions appeared on the screen and informed participants about the stimulus conditions and the task. Then there was a practice period of 24 trials. In the experimental phase, participants worked through 10 blocks of 24 trials each. There were two additional warm-up trials at the beginning of each block, which were not recorded.

A typical trial contained the following sequence of events. After a blank screen for 500 ms, the fixation point was presented at screen center for 500 ms. Then the stimulus display appeared for 500 ms, followed by another blank period of 500 ms. Response registration and reaction time (RT) measurement started with the onset of the stimulus display and lasted for 1,000 ms. Participants were instructed to respond to the color of either the square or the frame by pressing the left or right key as quickly as possible. Half of the participants pressed the left key to the green stimulus and the right key to the red stimulus; the other half responded with the opposite mapping. When a participant pressed the wrong key, or did not respond within one-second, a corresponding error message was shown on the screen for one-second. The whole session typically lasted about 15 min.

Design

The experiment had a 3 × 2 within-subjects design. The first variable was stimulus configuration, which had three levels (same-object condition, integrated-objects condition, and separate-objects condition, cf. Fig. 1). The second variable was spatial S–R correspondence, which had two levels. The irrelevant location of the square was either corresponding or noncorresponding to the location of the response to stimulus color. In each block, participants were presented with each combination of two colors (green vs. red), two frame positions (above or below the horizontal meridian), two square locations (to the left or right of the vertical meridian), and three stimulus configurations in random order.

Results

For this and the following experiments, median RT values were computed for each participant and condition. These values entered as dependent variable in analyses of variances (ANOVA). Additionally, *t* tests with an alpha level set to 0.05 were used for planned comparisons. Figure 2 shows the RT medians of correct responses for the six experimental conditions used in Experiment 1.

Response times

Median RTs of correct responses were subjected to a two-factorial ANOVA with stimulus configuration and spatial S–R correspondence as within-subjects variables. There was a significant main effect of the stimulus configuration, $F(2, 40) = 55.17$, MSE = 208.88, $p < .001$, indicating longer RTs for the same-object condition ($M = 417$ ms) compared with the integrated-objects condition ($M = 388$ ms) and to the separate-objects condition ($M = 388$ ms). There was also a significant main effect of spatial S–R correspondence, $F(1, 20) = 30.11$, MSE = 224.53, $p < .001$, demonstrating shorter RTs for spatially corresponding than for spatially noncorresponding conditions (390 vs. 405 ms). Finally, and most important, the two-way interaction was also significant, $F(2, 40) = 12.50$, MSE = 230.10, $p < .001$, indicating different effects of spatial S–R correspondence for the three stimulus configurations. In fact, two-tailed *t* tests revealed a significant Simon effect only for the same-object condition [difference (diff.) = 34 ms), $t(20) = 6.33$, $p < .001$. In contrast, there was neither a Simon effect in the integrated-objects condition (diff. = 5 ms), $t(20) = 1.19$, $p = .25$, nor in the separate-objects condition, (diff. = 5 ms), $t(20) = 1.19$, $p = .25$.

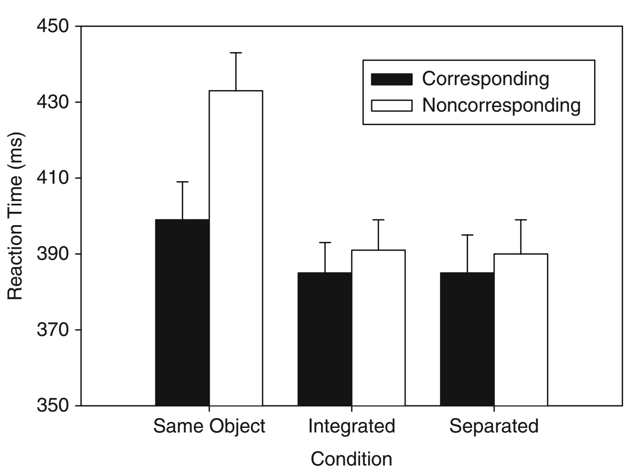

Fig. 2 Median RTs observed in Experiment 1. *Error bars* indicate standard errors between participants ($N = 21$)

Error percentages

An ANOVA on error percentages revealed a similar pattern of results as for RTs. First, a significant main effect of the stimulus configuration, $F(2, 40) = 22.97$, MSE = 8.74, $p < .001$, demonstrated more errors for the same-object condition ($M = 6.33\%$) compared with the integrated-objects condition ($M = 2.3\%$) and to the separate-objects condition ($M = 2.8\%$). Second, a significant main effect of spatial S–R correspondence, $F(1, 20) = 37.26$, MSE = 6.58, $p < .001$, indicated fewer errors for spatially corresponding than for spatially noncorresponding conditions (2.4 vs. 5.2%). Third, a significant two-way interaction, $F(2, 40) = 28.61$, MSE = 5.91, $p < .001$, indicated the selective occurrence of a Simon effect in error percentages for the same-object condition (diff. = 7.4%), $t(20) = 6.85$, $p < .001$. There was neither an effect of S–R correspondence in the integrated-objects condition (diff. = 0.6%), $t(20) = 1.21$, $p = .24$, nor in the separate-objects condition, (diff. = 0.4%), $t(20) = 0.61$, $p = .55$.

Discussion

In Experiment 1, the irrelevant location of a relevant object produced substantial Simon effects (34 ms, $p < .001$ in the same-object condition), whereas the location of an irrelevant object had no reliable effects on performance (non-significant Simon effects of 5 ms in both condition). These observations suggest that while observers encode the location of a task-relevant object, they do not regularly encode the location of irrelevant objects that are spatially close to the relevant object. Experiment 2 investigates whether and how increasing perceptual saliency of the irrelevant object increases its effect on performance.

Experiment 2

In Experiment 1, the location of a relevant square produced substantial Simon effects, whereas the location of an irrelevant square had negligible effects. One might argue, however, that participants did not process the location of the irrelevant square because it was less salient than the frame. In fact, we had attempted to make the square and the frame equally salient by matching the luminance of the different colors. However, the frame was larger than the square (i.e., the frame covered a larger area than the square), and the frame was more often the target than the square in Experiment 1. Both smaller size and lower relevance might have decreased the probability of processing the square when irrelevant. Therefore, Experiment 2 investigated whether the location of an irrelevant square would produce larger Simon effects when perceptual salience of the irrelevant square was increased. To achieve that, we presented the irrelevant object in white rather than in gray.

Method

Participants

Twenty new volunteers (16 women) with a mean age of 24 years (range from 20 to 35 years) participated for payment (5 Euro) or course credit.

Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 1. The only exception was that the uncolored stimulus was shown in white (luminance = 60 cd/m²) rather than in gray. As a result, the irrelevant stimulus (i.e., the frame in the same-objects condition, the square in the integrated-objects and in the separate-objects conditions) was much more salient in Experiment 2 than in Experiment 1.

Procedure

The procedure and design were the same as in Experiment 1.

Results

Response times

Figure 3 shows the median RTs of correct responses in the six experimental conditions in Experiment 2. Median RTs of correct responses were subjected to a two-factorial ANOVA with stimulus configuration and spatial S–R correspondence as within-subjects variables. The main effect of stimulus configuration was significant, $F(2, 38) = 50.11$, MSE = 243.31, $p < .001$, indicating longer RTs for the same-object condition ($M = 423$ ms) compared to the integrated-objects condition ($M = 391$ ms) and to the separate-objects condition ($M = 394$ ms). The main effect of spatial S–R correspondence was also significant, $F(1, 19) = 33.22$, MSE = 325.98, $p < .001$, demonstrating shorter RTs for spatially corresponding than for spatially noncorresponding conditions (393 vs. 412 ms). Finally, and most important, the two-way interaction was also significant, $F(2, 38) = 17.44$, MSE = 92.78, $p < .001$, indicating different Simon effects for the three configurations.

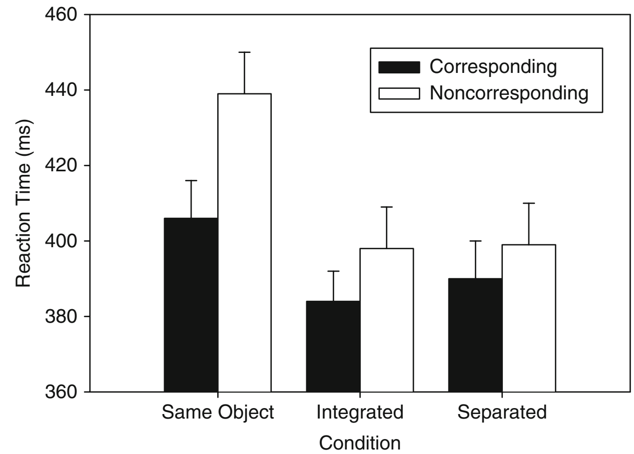

Fig. 3 Median RTs observed in Experiment 2. *Error bars* indicate standard errors between participants ($N = 20$)

Planned comparisons (two-tailed *t* tests) revealed significant Simon effects for all three conditions. There was a 33-ms Simon effect for the same-object condition, $t(19) = 7.11$, $p < .001$, a 15-ms Simon effect for the integrated-objects condition, $t(19) = 3.62$, $p < .01$, and a 9-ms Simon effect for the separate-objects condition, $t(19) = 2.52$, $p < .05$. Further comparisons revealed that the Simon effect was larger for the same-object condition than for the integrated-objects condition, $t(19) = 3.64$, $p < .01$, and for the separate-objects condition, $t(19) = 6.31$, $p < .001$, respectively. The latter two conditions did not differ, $t(19) = 1.50$, $p = .15$.

Error percentages

An ANOVA on error percentages revealed a similar pattern of results as for RTs. First, a significant main effect of stimulus configuration, $F(2, 38) = 23.52$, MSE = 7.95, $p < .001$, demonstrated more errors for the same-object condition ($M = 6.7\%$) compared to the integrated-objects condition

($M = 2.8\%$) and to the separate-objects condition ($M = 3.1\%$). Second, a significant main effect of spatial S–R correspondence, $F(1, 19) = 18.55$, $MSE = 20.98$, $p < .001$, indicated fewer errors for spatially corresponding than for spatially noncorresponding conditions (2.4 vs. 6.0%). Third, a significant two-way interaction, $F(2, 38) = 3.62$, $MSE = 11.84$, $p < .05$, revealed that Simon effects in error percentages varied across stimulus configurations.

Planned comparisons (two-tailed t tests) revealed significant Simon effects for the same-object condition (diff. = 5.9%), $t(19) = 3.75$, $p < .01$, for the integrated-objects condition (diff. = 1.9%), $t(19) = 2.22$, $p < .05$, and for the separate-objects condition (diff. = 3.0%), $t(19) = 2.69$, $p < .05$. Further comparisons revealed that the Simon effect was larger for the same-object condition than for the integrated-objects condition, $t(19) = 2.55$, $p < .05$, but similar to the Simon effect for the separate-objects condition, $t(19) = 1.56$, $p = .13$. The latter conditions did not differ, too, $t(19) = 1.03$, $p = .32$.

Discussion

The results of Experiment 2 basically replicated those of Experiment 1, although the higher perceptual saliency of the irrelevant objects increased the likelihood of processing these objects in Experiment 2. Again, the irrelevant location of a relevant object produced substantial Simon effects (33 ms, $p < .001$, in the same-object condition), whereas the location of an irrelevant object had smaller effects on performance (15 ms, $p < .01$, in the integrated-objects condition; 9 ms, $p < .05$, in the separated-objects condition). These observations again suggest that while observers regularly encode the location of a task-relevant object, they do not regularly encode the location of an irrelevant object even when the irrelevant object is perceptually more salient than the relevant one.

With regard to possible mechanisms for location coding, the results of Experiments 1 and 2 are consistent with the attention-shift account (e.g., Stoffer & Umiltà, 1997). Participants most likely performed spatial-attention shifts to the relevant square in the same-object condition, but participants did not have to shift attention to the relevant frame in the remaining condition because the frame appeared at a central location. Hence, the presence of attention shifts in the same-object condition and their absence in the remaining condition is consistent with the pattern of Simon effects. Moreover, the attention-shift account may even explain the (reduced) Simon effects in the integrated-objects condition by assuming that attention was sometimes diverted to the irrelevant square due to its high perceptual saliency. In contrast, the results are less consistent with the referential-coding account because there is no a priori reason for why there should be a limit in encoding the location of multiple objects simultaneously. Experiment 3 compares the role of attention shifts and referential coding for the encoding of object location more directly.

Experiment 3

Experiment 3 investigated more directly the relative contribution of spatial-attention shifts and referential coding for encoding the location of relevant and irrelevant objects. Therefore, displays were used in which the two mechanisms should produce different spatial codes for the relevant object and for the irrelevant object. As a result, the direction and size of Simon effects observed in the different conditions should inform us about which mechanism produced the stronger location code for the respective object.

There were three conditions in Experiment 3. In the square-relevant condition, participants responded to a colored square that now appeared at fixation, surrounded by a frame that was shifted either to the left or to the right of fixation (Fig. 4, left column). Importantly, in this condition, attention shifts should not produce a left/right code for the relevant square (or produce a neutral code), whereas the referential-coding system should encode the relative location of the relevant square in the frame. The direction and size of Simon effects in this condition should be informative with regard to the relative importance of attention shifts and referential coding for encoding the location of objects. Three outcomes are possible. If the relative location of the square within the frame produced a Simon effect, this would provide support for the referential-coding system. If the absolute location of the frame on the screen produced a Simon effect, suggesting that attention was drawn towards the center of the frame, this would provide support for attention shifts. If, however, no Simon effects were observed, two explanations were possible. The absence of Simon effects could either indicate that neither mechanism was active, or that both mechanisms produced opposite codes of equal strength.

In the frame-relevant condition, participants responded to the colored frame that appeared at the left or right location and included a white square at fixation (Fig. 4, central column). In this condition, attention shifts and referential coding should produce similar codes for the relevant frame. The question with regard to the frame-relevant condition was whether the presence of the irrelevant square would affect location coding of the relevant frame at all. To assess the effects of the irrelevant square, performance in the frame-relevant condition was compared to performance in a frame-only condition (Fig. 4, right column). If anything, processing of the irrelevant square should reduce any Simon effects with regard to the location of the relevant frame for at least two reasons. First, the presence of the

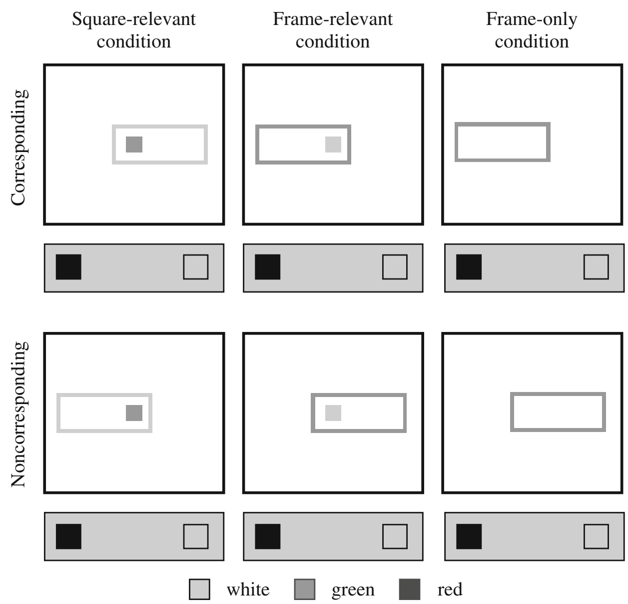

Fig. 4 Example of a stimulus–response configuration for each of the six experimental conditions in experiment. The S–R mapping depicted in the present example is *green-left* and *red-right*. For simplicity, only responses to *green stimuli* are depicted. S–R correspondence refers to the relationship between the irrelevant location of the colored stimulus (i.e., the square in the square/frame condition; the frame in the remaining conditions) and the location of the keypress response. A *black key* indicates the correct response key

irrelevant square might interfere with attention shifts towards the center of the frame. Second, referential coding might produce a code for the irrelevant square that counteracts the effect of the location code for the frame because the two objects have opposite (relative) locations.

Method

Participants

Seventeen new volunteers (14 women) with a mean age of 24 years (range from 20 to 28 years) participated for payment (5 Euro) or course credit.

Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 2, except for the fact that the square and the frame were presented at different locations. In particular, the square was always presented at screen center. In contrast, the position of the frame was shifted to the left or to the right, but the frame always included the screen center. There were three basic stimulus configurations in Experiment 3 (Fig. 4). In the square-relevant condition, a green or red square appeared at screen center, framed by a white rectangle that was shifted to the left or to the right of the center (Fig. 4, left column). In the frame-relevant condition a white square appeared at screen center, framed by a green or red rectangle that was shifted to the left or right of the center (Fig. 4, central column). In the frame-only condition, a red or green frame appeared alone at the left or right position (Fig. 4, right column).

Procedure

At the beginning of the experiment, the instructions appeared on the screen and informed participants about the stimulus conditions and the task. Then there was a practice period of 36 trials. In the experimental phase, participants worked through 10 blocks of 36 trials each. There were two additional warm-up trials at the beginning of each block, which were not recorded. A complete session lasted about 15 min. The sequence of events in a typical trial was the same as in Experiment 2.

Design

The experiment had a 3 × 2 within-subjects design. The first variable was stimulus configuration, which had three levels (i.e., square-relevant condition, frame-relevant condition, frame-only condition; see Fig. 4). The second variable was S–R correspondence, which referred to the spatial correspondence between the relevant stimulus and the response. In the square-relevant condition, the relative location of the colored square within the frame was corresponding or noncorresponding to response location. In the frame-relevant condition and in the frame-only condition, the location of the colored frame was corresponding or noncorresponding to the location of the response. Each combination of the different levels of the three experimental variables was presented in random order to the participants.

Results

Response times

Figure 5 shows the median RTs of correct responses for the 6 experimental conditions in Experiment 3. Median RTs of correct responses were subjected to a two-factorial ANOVA with stimulus configuration and S–R correspondence as within-subjects variables. The main effect of stimulus configuration was significant, $F(2, 32) = 35.71$, MSE = 92.32, $p < .001$, indicating longer RTs for the square-relevant condition ($M = 392$ ms) compared to the frame-relevant condition ($M = 377$ ms) and to the frame-only condition ($M = 374$ ms). The significant main effect of S–R correspondence, $F(1, 16) = 30.70$, MSE = 92.11, $p < .001$, was further qualified by a significant two-way

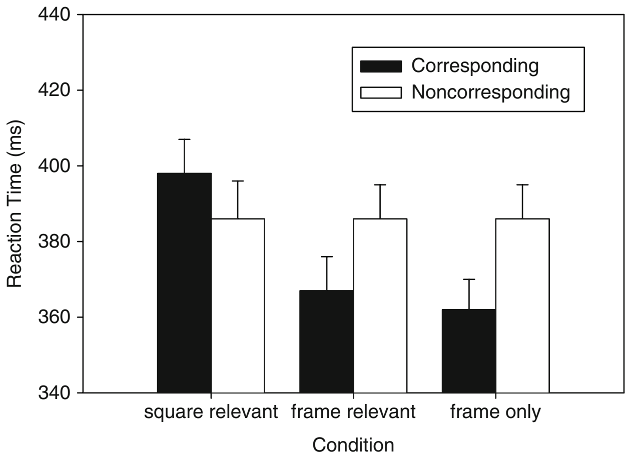

Fig. 5 Median RTs observed in Experiment 3. *Error bars* indicate standard errors between participants ($N = 17$)

interaction, $F(2, 32) = 25.08$, MSE = 122.18, $p < .001$. The interaction referred to the observation of an inverted Simon effect for the square-relevant condition, compared to normal Simon effects for the frame-relevant and the frame-only conditions (Fig. 5). When the square was the relevant object, participants were faster with noncorresponding conditions ($M = 386$ ms) than with corresponding conditions ($M = 398$ ms), $t(16) = 3.38$, $p < .01$. In contrast, in the frame-relevant condition, participants were faster with corresponding conditions ($M = 367$ ms) than with noncorresponding conditions ($M = 386$ ms), $t(16) = 5.88$, $p < .001$. Similarly, in the frame-only condition, participants were also faster with corresponding conditions ($M = 362$ ms) than with noncorresponding conditions ($M = 386$ ms), $t(16) = 5.59$, $p < .001$. Finally, the Simon effects in the frame-relevant condition (diff. = 19 ms) and in the frame-only condition (diff. = 24 ms) did not differ, $t(16) = 1.43$, $p = .17$.

Error percentages

Error percentages were subjected to a two-factorial ANOVA with stimulus configuration and S–R correspondence as within-subjects variables. The main effect of stimulus configuration was not significant ($F < 1$). Similar to the RT analysis, however, there was a significant main effect of S–R correspondence, $F(1, 16) = 7.36$, MSE = 7.14, $p < .05$, which was further qualified by a significant two-way interaction, $F(2, 32) = 5.28$, MSE = 7.97, $p < .05$. The interaction referred to the selective occurrence of a significant Simon effect for the frame-relevant condition. Please note, however, that the numerical error pattern was compatible with the RT results. In fact, when the square was the relevant object, the error percentage was higher with corresponding ($M = 4.2\%$) than with noncorresponding conditions ($M = 3.3\%$), $t(16) = 1.14$, $p = .27$. In the frame-relevant condition, the error percentage was lower with corresponding ($M = 1.6\%$) than with noncorresponding conditions ($M = 5.1\%$), $t(16) = 5.46$, $p < .001$. Finally, in the frame-only condition, the error percentage was numerically lower with corresponding ($M = 2.2\%$) than with noncorresponding conditions ($M = 3.8\%$), $t(16) = 1.28$, $p = .22$.

Discussion

Experiment 3 produced two main results. First, when participants responded to the colored square presented at fixation and surrounded by a frame, the direction of the Simon effect was inconsistent with the relative location of the square within the frame, but the Simon effect was consistent with the absolute location of the irrelevant frame on the screen. This result suggests that attention shifts were more important than referential coding for producing spatial codes in this condition. In particular, because the square was presented at fixation, attention shifts should not produce a lateral code for that stimulus. The fact that the absolute location of the irrelevant frame produced a Simon effect suggests that attention was drawn from the screen center towards the center of the frame, producing a Simon effect. The results are not consistent with the referential-coding account. The reason is that when the referential-coding system encodes the absolute location of the irrelevant frame, it should also encode the relative location of the relevant square within the frame. Because the code for the relevant object should be at least as strong as the code for the irrelevant object, the referential-coding account cannot explain why the location of the irrelevant frame had more impact than the location of the relevant square within the frame.

The second main result was obtained in the frame-relevant and frame-only conditions. In particular, when participants responded to the colored frame, the location of the frame on the screen produced a Simon effect. Moreover, presenting an irrelevant square inside the frame at a relative location that was incongruent to the location of the frame did not significantly affect the Simon effect of frame location. These results again appear to be more consistent with the attention-shift account than with referential coding. The attention-shift account explains the results in assuming that, regardless of whether a square was presented at fixation or not, spatial attention was pulled towards the center of the relevant frame, and the resulting spatial code produced a Simon effect. In contrast, the referential-coding account has more difficulties to explain the results. In particular, when the referential-coding system was active and encoded the absolute location of the frame, it is difficult to see why it did not also encode the relative location of the square. In summary, the results of Experiment 3 suggest that attention shifts are more important for encoding the task-irrelevant location of an object than are referential-coding processes.

Experiment 4

Experiment 4 explored the limits for encoding the location of irrelevant objects. Participants always responded to the color of a frame that appeared at screen center and that was tilted to the left or to the right (Fig. 6). The irrelevant object was a white diamond that appeared inside (integrated condition), or outside (separated condition) the frame. We varied spatial S–R correspondence between the horizontal location of the irrelevant diamond and the location of the response to the frame. Moreover, we manipulated the asynchrony (SOA) between the onset of the irrelevant location information and the onset of the relevant color information. Therefore the frame always appeared first on the screen in gray color, and subsequently changed its color to red or green. The onset of the irrelevant diamond was varied with regard to the color change of the frame. The diamond preceded color onset by 150 ms (SOA = −150 ms), or the diamond appeared simultaneously with color onset (SOA = 0 ms), or the diamond followed color onset by 150 ms (SOA = 150 ms).

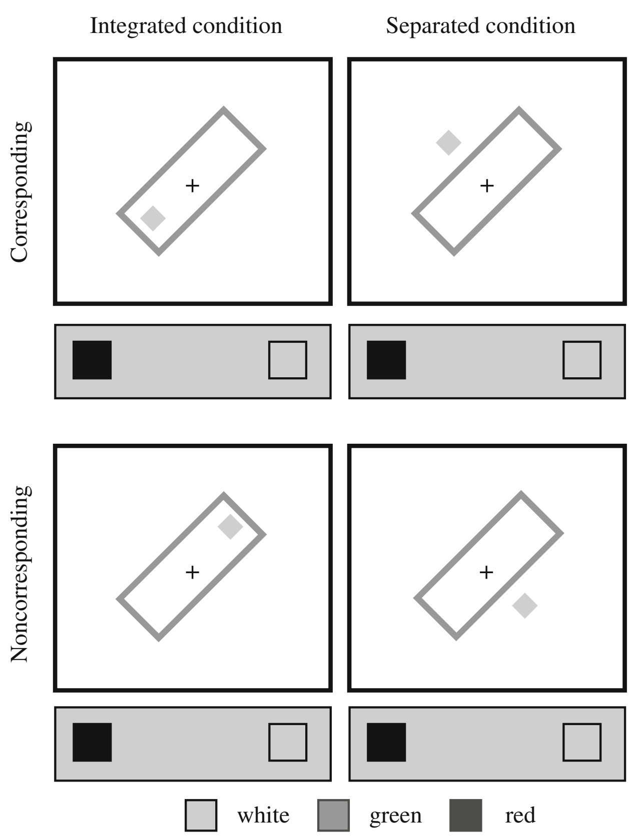

Fig. 6 Example of stimulus–response configurations with simultaneous onset of the irrelevant diamond and the relevant frame in Experiment 4. The S–R mapping depicted in the present example is *green-left* and *red-right*. For simplicity, only responses to *green stimuli* are depicted. S–R correspondence refers to the relationship between the horizontal location of the irrelevant diamond and the location of the keypress response. A *black key* indicates the correct response key

Three features of the design were expected to increase the likelihood of the irrelevant object being processed. First, the white diamond was brighter than the colored frame. Second, the unique onset of the diamond should increase its power for attracting attention. Third, temporal uncertainty about the onset of the diamond might also increase its chances for being processed. At the same time, varying the SOA between the onset of the diamond and the onset of the relevant color stimulus provides a means for assessing the time course of location processing. In particular, the irrelevant object might have the largest impact when appearing simultaneously with the color stimulus. When the diamond precedes the color stimulus, the stimulus-location code may decay to some degree until the color stimulus arrives (e.g., Hommel, 1993b). When the diamond follows the color stimulus, color processing has a head start.

Method

Participants

Twenty-four new volunteers (21 women) with a mean age of 23 years (range from 19 to 31 years) participated for payment (5 Euro) or course credit.

Apparatus and stimuli

We used the same apparatus as in the preceding experiments. The relevant stimulus was a rectangle (frame) measuring 10.8° in length and 3.4° in height. The frame was presented at screen center in a diagonal orientation (i.e., tilted 45° to the left or to the right of the vertical meridian). The irrelevant stimulus was a filled white diamond with a side length of 0.9°. The diamond was presented 3.7° to the lower left, the upper left, the upper right, or the lower right of screen center—depending upon the stimulus configuration. The distance between the edge of the diamond and the vertical meridian of the screen was 20 mm (2.3°).

When compared to Experiments 1 and 2, we changed both the orientation of the relevant frames and the orientation of the irrelevant squares. The reason for this change was that we wanted to present the relevant frames at fixation and simultaneously avoid confounding the orientation of the relevant object with stimulus configuration (i.e., whether irrelevant objects appeared inside or outside the relevant objects). Presenting the relevant frames tilted either 45° to the left or right of the vertical meridian allowed us to present the irrelevant objects (i.e., diamonds) at the same locations regardless of whether they appeared inside or outside the frames.

There were two basic stimulus configurations in Experiment 4 (Fig. 6). In the integrated condition the white diamond appeared inside the frame at one of the short sides. In the separated condition the white diamond appeared outside the frame at one of the long sides. All visual stimuli were presented on a black background.

Procedure

At the beginning of the experiment, the instructions appeared on the screen and informed participants about the stimulus conditions and the task. Then there was a practice period of 48 trials. In the experimental phase, participants worked through 10 blocks of 48 trials each. There were two additional warm-up trials at the beginning of each block, which were not recorded. A complete session lasted about 30 min.

The sequence of events in a trial began with a clear screen for 500 ms, followed by presentation of the fixation mark at screen center for 500 ms. Next, the tilted frame was added to the display in gray color and stayed there for 500 ms. Then the frame changed its color to green or red and remained for 1,000 ms or until a response had occurred. Participants were instructed to press the left or right control key on a standard keyboard as quickly as possible to the color of the frame. Depending on the SOA condition, the white diamond appeared 150 ms before the color change, or simultaneously with the color change, or 150 ms after the color change, and stayed as long as the frame and the fixation point (i.e., until a response had occurred or after 1,000 ms had elapsed). The procedure followed those of the preceding experiments in each other respect.

Design

The experiment had a 2 × 3 × 2 within-subjects design. The first variable was stimulus configuration, which had two levels (i.e., integrated condition vs. separated condition; see Fig. 6). The second variable was the SOA between the onset of the diamond and the onset of the color change with three levels (−150 ms: diamond preceded color change; 0 ms: simultaneous onset; 150 ms: diamond followed color change). The third variable was S–R correspondence (corresponding vs. noncorresponding), which referred to the spatial correspondence between the location of the irrelevant white diamond and the response to the colored frame. Each combination of the different levels of the three experimental variables was presented in random order to the participants.

Results

Response times

Figure 7 shows the median RTs of correct responses for the 12 experimental conditions in Experiment 4. Median RTs of correct responses were subjected to a three-factorial ANOVA with stimulus configuration, SOA, and S–R correspondence as within-subjects variables. The main effect of stimulus configuration was not significant, $F(1, 23) = 1.54$, MSE = 111.25, $p = .23$. However, the main effect of SOA was significant, $F(2, 46) = 45.70$, MSE = 307.47, $p < .001$, demonstrating shorter RTs when the diamond appeared before ($M = 394$ ms) or simultaneously with the color stimulus ($M = 388$ ms) than when it followed the color stimulus ($M = 411$ ms). A significant main effect of S–R correspondence, $F(1, 23) = 21.22$, MSE = 173.57, $p < .001$, demonstrated shorter RTs with corresponding than with noncorresponding (394 vs. 401 ms) conditions. The only significant interaction occurred between SOA and S–R correspondence, $F(2, 46) = 6.44$, MSE = 105.49, $p < .01$, indicating that Simon effects varied across SOA levels (all other interactions: $F < 1$). Separate two-way ANOVAs revealed significant Simon effects when the diamond preceded the color stimulus (390 vs. 398 ms), $F(1, 23) = 9.73$, MSE = 160.29, $p < .01$, and when the diamond appeared simultaneously with the color stimulus (382 vs. 394 ms), $F(1, 23) = 35.58$, MSE = 96.46, $p < .001$. In contrast, there was no Simon effect when the diamond followed the color stimulus (411 vs. 412 ms), $F(1, 23) < 1$, $p = .54$.

Error percentages

A three-factorial ANOVA on error percentages revealed a significant main effect of SOA, $F(2, 46) = 7.71$, MSE = 7.04,

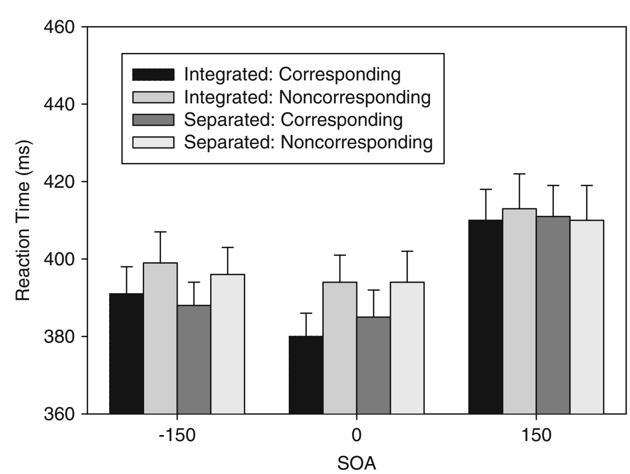

Fig. 7 Median RTs observed in Experiment 4. *Error bars* indicate standard errors between participants ($N = 24$)

$p < .01$, and a significant interaction between SOA and stimulus configuration, $F(2, 46) = 4.33$, MSE = 3.93, $p < .05$. The main effect of SOA meant that errors decreased across SOA levels (from 3.6, 2.5, to 2.1%). The interaction indicated that the decrease of errors across SOA was more pronounced for diamonds outside the frame (4.0, 2.6, 1.7%) than for diamonds inside the frame (3.1, 2.5, 2.5%). None of the remaining *F* tests was significant (all $F < 1.2$, all $p > .25$).

Discussion

The results of Experiment 4 again demonstrated very small Simon effects from the horizontal location of an irrelevant object, even though we attempted to make the processing of the irrelevant object as likely as possible. In particular, the irrelevant object was brighter than the relevant object, it had a unique onset in the visual field, and its onset was temporally unpredictable. Nevertheless, the location of the irrelevant object produced Simon effects of less than 10 ms, which is not larger as in the preceding experiments, and clearly smaller than Simon effects resulting from the location of a relevant object. These results suggest that the location of an irrelevant object is processed less efficiently, even when being very salient.

One might ask why the irrelevant stimuli were not more effective in producing a Simon effect even though we attempted to make them as salient as possible. Note, however, that the frame always appeared (in gray color) before the diamond and the diamond was never a relevant stimulus in Experiment 4. These conditions most likely allowed participants to effectively focus their spatial attention onto the relevant stimulus (i.e., the frame) well before the irrelevant location stimulus appeared, preventing the irrelevant object from capturing spatial attention in the large majority of trials. These results are fully consistent with previous studies demonstrating that the opportunity to focus spatial attention onto a relevant location can prevent an irrelevant stimulus having an abrupt visual onset somewhere else to capture attention (e.g., Yantis & Jonides, 1990).

General discussion

The purpose of our study was twofold. One purpose was to further explore the mechanisms of location coding in the Simon task. Another purpose was to assess the automaticity of location processing by comparing the effects of processing the location of relevant objects to the effects of processing the location of irrelevant objects.

In Experiments 1 to 3, participants responded to the color of one of two objects, a rectangular frame or a square, with a lateral keypress, and we varied spatial S–R correspondence between the locations of the objects and the location of the response. In Experiments 1 and 2, the frame always appeared at a central location, whereas the horizontal location of the square varied randomly from trial to trial. In both experiments, we observed strong Simon effects from square location when participants responded to the square, while we found negligible Simon effects from square location when participants responded to the frame. Participants always responded to the frame in Experiment 4, and the results replicated the negligible Simon effects from the location of an irrelevant square even though the square had a unique and temporally unpredictable onset in the display. Finally, in Experiment 3, the square always appeared at a central location, whereas the horizontal location of the frame varied randomly from trial to trial. Results demonstrated an inverted Simon effect from relative square location within the frame when participants responded to the square, which corresponds to a Simon effect from absolute frame location on the screen. In contrast, we observed normal Simon effects from absolute frame location when participants responded to the frame, and the presence of a square within the frame did not affect these effects.

The present set of results clearly shows that the location of an irrelevant object in the visual field is processed to a much smaller extent than the location of a relevant object. To be more precise, the location of relevant objects produced significant Simon effects of about 33 ms in Experiments 1 and 2, whereas the location of irrelevant objects produced Simon effects of only 9 ms, on average, which were not always significant. Moreover, our attempts to increase the likelihood of processing the irrelevant object in Experiment 4 failed because the location of the irrelevant object still produced Simon effects of only 7 ms in that experiment. Together, the results demonstrate that human observers are quite effective in restricting their attention on a relevant object, even though they tend to process both relevant and irrelevant features of the attended object (e.g., Duncan, 1984). The pattern of results observed here with the Simon task is consistent with findings from other filtering tasks, as the Eriksen flanker task (e.g., Kramer & Jacobson, 1991) or the Stroop task (e.g., Wühr & Waszak, 2003).

Two mechanisms have been proposed to explain the formation of a spatial stimulus code in the Simon task, attention shifts and referential coding. According to the former account, the direction of an attention shift to the location of the imperative stimulus produces the location code that activates a spatially corresponding response code (see, Stoffer & Umiltà, 1997, for a review). In contrast, according to the latter account, a special mechanism encodes the relative location of the imperative stimulus with regard to a salient reference stimulus as, for example, the fixation point (Hommel, 1993a). The results of Experiments 1 and 2 are consistent with the attention-shift account. The lateral location of the square produced much larger Simon effects when it was relevant because attention was shifted much more often to a relevant square than to an irrelevant square. In contrast, the small or negligible Simon effect with the central frame as the relevant object appears less consistent with the referential-coding account for two reasons. First, there is no a priori reason to assume a limit in the encoding of multiple objects simultaneously. In other words, one could have expected encoding of the irrelevant square with regard to the relevant frame. Second, one could have also expected lateral location of the irrelevant square to affect localization of the relevant frame, producing a trend towards an inverted Simon effect. However, it is possible to reconcile the referential-coding account with the results of Experiments 1, 2 and 4 by assuming that relevant objects produce much stronger spatial codes than irrelevant objects.

The results of Experiment 3 provide more direct support for the attention-shift account, however. In this experiment, participants either responded to a central square or to a lateral frame. Results demonstrated an inverted Simon effect with regard to the relative location of the relevant square within the frame, and normal Simon effects with regard to the absolute location of the relevant frame on the screen. The attention-shift account can explain the results in assuming that the focus of spatial attention was drawn towards the center of the frame regardless of whether it was relevant or not. In contrast, the referential-coding account has particular problems in explaining the inverted Simon effects with the central square as the relevant stimulus. Referential coding should have preferentially encoded the relative location of the relevant square within the surrounding frame, and this process should have produced a normal Simon effect of relative square location, but the opposite result was obtained. Thus, to summarize, it seems fair to conclude that the attention-shift account is more consistent with the present pattern of results than is the referential-coding account.

What do the present results tell us about the automaticity of location processing in the Simon task? As described in the Introduction, the Simon effect is commonly seen as arising from two consecutive steps of automatic processing (e.g., Lu & Proctor, 1995; Stoffer & Umiltà, 1997). In a first step, the irrelevant location stimulus is encoded; in a second step the stimulus-location code activates a spatially corresponding response code. The present study is concerned with the question of whether the first step (i.e., the encoding of stimulus location) runs in an automatic fashion or not. The literature provides two major criteria for an automatic process: insensitivity from manipulations of processing load and independence from the intentions of the observer (e.g., Posner & Snyder, 1975; Yantis & Jonides, 1990). The present study investigated whether the encoding of stimulus locations is independent from the observers' intentions (Müsseler, Wühr, & Umiltà, 2006, for an investigation of the load-insensitivity criterion). In particular, we investigated whether observers encode only the (irrelevant) locations of relevant (i.e., attended) objects or whether observers also encode the (irrelevant) locations of irrelevant (i.e., unattended) objects. The results of the present study suggest that observers encode the location of an irrelevant object to a much lesser degree than the location of a relevant object, demonstrating that intentions have a large effect on location processing. Thus, location processing in the Simon task is certainly not strongly automatic.

The residual Simon effects resulting from the location of an irrelevant object that were observed in the present Experiments 2 and 4 might indicate that location processing is at least partly automatic, in the sense that participants cannot completely avoid encoding the location of irrelevant objects. However, the question is whether complete control is to be expected in a situation like those in the present experiments. Note that the experimental conditions made the task of ignoring the irrelevant objects quite difficult. First, in Experiments 1 and 2, the to-be-ignored shape in a given trial was a relevant stimulus in other trials of the same experiment. Second, the to-be-ignored stimulus was perceptually more salient (in terms of luminance) than the relevant stimulus in Experiments 2 and 4. Interestingly, the irrelevant object failed to produce a Simon effect in Experiment 1, whereas the irrelevant object produced residual Simon effects in Experiments 2 and 4. This pattern of results suggests that participants found it more difficult to ignore a perceptually very salient stimulus (in Experiments 2 and 4) than to ignore an occasionally relevant stimulus (in Experiment 1).

To summarize, the present set of results demonstrate that location-based response activation in the Simon task is not strongly automatic, as was suggested by Kornblum et al. (1990). A cognitive process is defined as strongly automatic if it runs independent from the current intentions of the observer (e.g., Kahneman & Treisman, 1984). The present results demonstrate, however, that intentions play a role for the processing of stimulus location because the location of a relevant object is encoded to a much stronger degree than the location of an irrelevant object.

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