Testing the boundary conditions for processing irrelevant location information: The cross-task Simon effect

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The Simon effect denotes superior performance when stimulus and response positions correspond than when they do not, even when stimulus position is irrelevant. Usually, this effect is attributed to the automatic formation of a spatial stimulus code that interferes with response selection. Recent evidence, however, called the hypothesis of automatic processing of stimulus position into question. The present study aimed at providing a strong test of this hypothesis. In two experiments, a dual-task procedure was employed. The primary task was an auditory-manual four-choice task (S1–R1 task). The secondary task was a visual encoding task (S2–R2 task), and S2 followed S1 with a variable stimulus onset asynchrony (SOA). Horizontal position of S2, which was irrelevant for both tasks, was also varied, and the effect of spatial S2–R1 correspondence was investigated. Experiment 1 showed dual-task impairment in visual encoding, and a cross-task Simon effect at short SOAs. That is, S2 position affected R1 selection, although less capacity was available for deliberately processing S2 position. In addition, Experiment 2 revealed the absence of the cross-task Simon effect when the target appeared simultaneously with a contralateral distractor. Together, the results suggest that encoding of stimulus position can run automatically, on the basis of an exogenous attention shift towards stimulus location.

The spatial correspondence or noncorrespondence between stimuli and responses has marked effects upon spatial behaviour. If, for example, participants respond to the location of stimuli with responses at different locations, spatially compatible conditions (left S–left R vs. right S–right R) allow for faster and more accurate responses than spatially incompatible conditions (left S–right R vs. right S–left R; e.g., Nicoletti & Umiltà, 1984). Importantly, the spatial relationship between stimuli and responses still affects performance when stimulus position is actually irrelevant for the task. If, for example, participants press a left key to green stimuli and a right key to red stimuli, and these stimuli appear randomly to the left or right of fixation, then spatially corresponding conditions (left green S and right red S) produce better performance than spatially noncorresponding conditions (right green S and left red S; e.g., Simon & Berbaum, 1990). The latter observation is called the Simon effect (Hedge & Marsh, 1975; see Lu & Proctor, 1995, for a review). Investigations of spatial S–R compatibility effects reveal important insights into the principles of human action control (cf. Hommel & Prinz, 1997; Proctor & Reeve, 1990).

Dominating accounts of the Simon effect are often referred to as two-route models (e.g., Hommel, 1997; Kornblum, Hasbroucq, & Osman, 1990; Zhang, Zhang, & Kornblum, 1999; Zorzi & Umiltà, 1995). These models distinguish two parallel routes of response selection in the Simon task. An indirect route processes the relevant stimulus feature (i.e., colour) and activates the correct response, according to the instructions. Simultaneously, stimulus location is assumed to activate the spatially corresponding member of the current response set through a direct route. In corresponding conditions, both routes produce the same output, and the correct response is quickly executed. In noncorresponding conditions, however, the routes produce different outputs, and a response conflict delays responding.

It is widely believed that position-based response activation through the direct route is an *automatic* process (e.g., Kornblum et al., 1990; Zhang et al., 1999). Automatic processes are defined as being independent of processing capacity (e.g., attention), and also to run independent from the current intentions of the individual (cf. Brown, Gore, & Carr, 2002; Posner & Snyder, 1975; Shiffrin & Schneider, 1977). It is often claimed that the results of electrophysiological studies, showing that task-irrelevant stimulus location can activate spatially corresponding hand areas in primary motor cortex (PMC) of humans (e.g., De Jong, Liang, & Lauber, 1994), support the idea that position-based response activation in the Simon task runs automatically. However, Valle-Inclan and Redondo (1998) observed that stimulus position did not activate spatially corresponding hand areas in PMC, when participants did not know the relevant S–R mapping for the upcoming trial (see also Valle-Inclan, Hackley, & de Labra, 2002). This result suggests that effects of stimulus location upon motor areas are somehow related to the participants' intentions (cf. Ansorge & Wühr, 2004). Hence this result casts doubts on the automatic character of position-based response activation.

If position-based response activation in the Simon task is not automatic, why does it occur at all? There are at least two possible answers to this question. The first answer might be that, in the typical Simon task, relevant stimulus information (e.g., colour) and irrelevant position information belong to the same perceptual object. There is some empirical evidence suggesting that irrelevant features of a relevant, and hence attended, object is processed obligatorily, which does not apply to the features of irrelevant objects (e.g., Behrmann, Zemel, & Mozer, 1998; Duncan, 1984). For example, Wühr and Waszak (2003) observed that irrelevant colour words more strongly affected the task of naming the colour of rectangles, when the words were part of the relevant object than when they were not. Hence the question is whether the Simon effect still occurs when the response-relevant stimulus information and the irrelevant position information belong to different perceptual objects.

The Simon effect still occurs when the relevant information and the irrelevant position information are perceptually separated in space and/or time. In the so-called accessory-stimulus version of the Simon task (Proctor & Pick, 1998), participants are presented with two different stimuli, and the relevant stimulus is spatially neutral with respect to the responses, while the location of the irrelevant stimulus is varied. Using this methodology, several studies found that the location of a monaurally presented tone produces Simon effects in responses to visual stimulation (e.g., Bernstein & Edelstein, 1971; Simon & Craft, 1970). In face of these results, one might argue that contiguous presentation of the different stimulus events makes them being integrated into one perceptual event, and the Simon effect arises because irrelevant location information belongs to the same perceptual event as the relevant information. Yet this argument is weak because further studies observed Simon effects, when the relevant information was provided first, and the irrelevant location information followed much later, for example, as part of a go signal (e.g., Hommel, 1996; Shiu & Kornblum, 1999). This observation suggests that the irrelevant spatial information remains effective even when it belongs to a different spatial event.

The second possible explanation for deliberate processing of stimulus location in the Simon task refers to its modest difficulty. Usually the Simon effect is investigated in very simple two-choice tasks, in which the participants' processing capacity is not fully required. Therefore, irrelevant location information might be processed because the primary task leaves enough capacity for doing this, and not because processing stimulus location requires no capacity at all (cf. for a similar idea Lavie, 1995).

The limits of processing capacity can be explored in dual-task situations. The best known dual-task paradigm is the psychological-refractory-period (PRP) paradigm. In the PRP paradigm, as introduced by Telford (1931), two stimuli—S1 and S2—are presented and the stimulus–onset asynchrony (SOA) between S1 and S2 is varied. The participants' task is to perform distinct responses to each stimulus, as quickly as possible. Typically, SOA has only little effects upon reaction times (RT) to S1, that is, upon RT1. Yet RT2 increases considerably with decreasing SOA, constituting the PRP effect (see Pashler, 1994, 1998, for reviews). The typical interpretation is that S1 is processed before S2 and, therefore, processing S2 does not affect processing S1. Conversely, however, the processing of S1 prevents particular limited-capacity processing stages from being used for processing S2. As a result, processing of S2 has to wait until the critical stages have finished processing S1. Experimental findings suggest that the central stage of response selection is limited to process one event at a time (cf. Pashler, 1984, 1994).

More recent dual-task studies found evidence that processing S1 not only impairs the selection of R2, but also impairs perceptual encoding of S2. For example, Jolicoeur (1999) combined a speeded two-choice response task with an unspeeded perceptual-discrimination task, and observed a PRP effect in discrimination accuracy for S2. Obviously, processing of S1 requires limited-capacity stages that are also needed for the encoding of S2. Müsseler and Wühr (2002) replicated these results and further demonstrated, by using a go/nogo manipulation in the primary task, that both perceptual and postperceptual processing of S1 interferes with encoding of S2 (see also Danielmeier, Zysset, Müsseler, & Cramon, 2004). Together, these studies demonstrate that, in dual-task situations, primary choice-response tasks afford the capacity of processing stages that are also needed for encoding of S2 (see also Koch, Metin, & Schuch, 2003; Koch & Prinz, 2002). Therefore, such dual-task paradigms seem well suited for investigating the question of whether the irrelevant location of a stimulus (S2) still affects the preparation of a response (R1), when R1 is given to a different stimulus (S1), and the task leaves only little capacity for processing S2.

Preliminary evidence comes from a dual-task study by Koch et al. (2003). In this study a visual encoding task was combined with an auditory-manual choice RT task. The relevant feature of the visual stimulus (S1) was its spatial position, and this position produced cross-task compatibility effects (i.e., faster responses) when S1 and R2 spatially corresponded (see also Koch & Prinz, 2002). But in this study, spatial position was nominally relevant for the visual encoding task. However, a cross-task Simon effect would be characterised by the irrelevant spatial stimulus information in both tasks.

In fact, there is only one previous study that investigated the possibility of S2–R1 Simon effects in a dual-task situation. In their study, Lien and Proctor (2000) had participants respond to S1 with two fingers of one hand, and to respond to S2 (an arrowhead) with two fingers of the other hand. The authors varied the SOA between S1 and S2, the mapping between S2 and R2 (compatible or incompatible), and the location of S2 (left or right). The interesting question in the present context is whether the irrelevant location of S2 affected

R1. With respect to that question, the Lien and Proctor study revealed somewhat puzzling results. First, when S1 was auditory, their Experiment 2 revealed an S2–R1 Simon effect, but only for the compatible S2–R2 mapping. Second, when S1 was visual, their Experiment 3 revealed no S2–R1 effect with the compatible mapping, but there was an inverted S2–R1 Simon effect with the incompatible mapping. In sum, the Lien and Proctor study did not reveal clear evidence for the automaticity of position-based response activation. Rather, in this study, the effects of irrelevant location information seemed to be modulated by intentions, that is, the relevant S2–R2 mapping. Yet, several aspects of the Lien and Proctor task render the interpretation of their results difficult with respect to the main question of the present study. Firstly, there is a possible source of interference between the relevant feature (arrowhead direction) and the irrelevant feature (location) of S2. Secondly, the S1–R1 task seems relatively easy and S2 was not masked, which makes it unlikely that processing of S2 encountered severe capacity limitations.

The aim of the present study was to investigate location-based response activation under conditions in which controlled processing of stimulus location seems unlikely. In particular, we investigated whether the location of S2 would still affect R1 when (1) the location of S2 was irrelevant for both tasks, and (2) the processing of task-relevant information was highly demanding, leaving little or no capacity for processing S2 location. Therefore, a speeded four-choice response task was combined with the difficult perceptual encoding task. If the irrelevant location of S2 would still affect R1 under these conditions, producing a cross-task Simon effect, we might conclude that this effect was really due to automatic processing.

EXPERIMENT 1

Experiment 1 investigated whether the position of a stimulus S2 is still processed when the position of S2 is irrelevant, S2 requires no spatial response, and there is little capacity left for processing S2 position. The experiment employed a dual-task procedure. In the primary task, participants responded manually to the number and pitch of an auditory S1. For example, two low-pitch tones required a short key press with the left hand, and one high-pitch tone required a long key press with the right hand. S1 was followed by S2 with a variable SOA. S2 was a circle with two gaps, which were either horizontally or vertically oriented (Figure 1). Participants had to discriminate and report the orientation of the gaps. To increase the difficulty of the discrimination task, S2 was presented briefly and followed by a mask.

Most importantly, we also varied the horizontal position of S2 and, by doing this, established spatial correspondence or noncorrespondence between S2 and R1. The main question was whether irrelevant S2 location would affect the execution of R1 under these conditions. That is, would a cross-task Simon effect

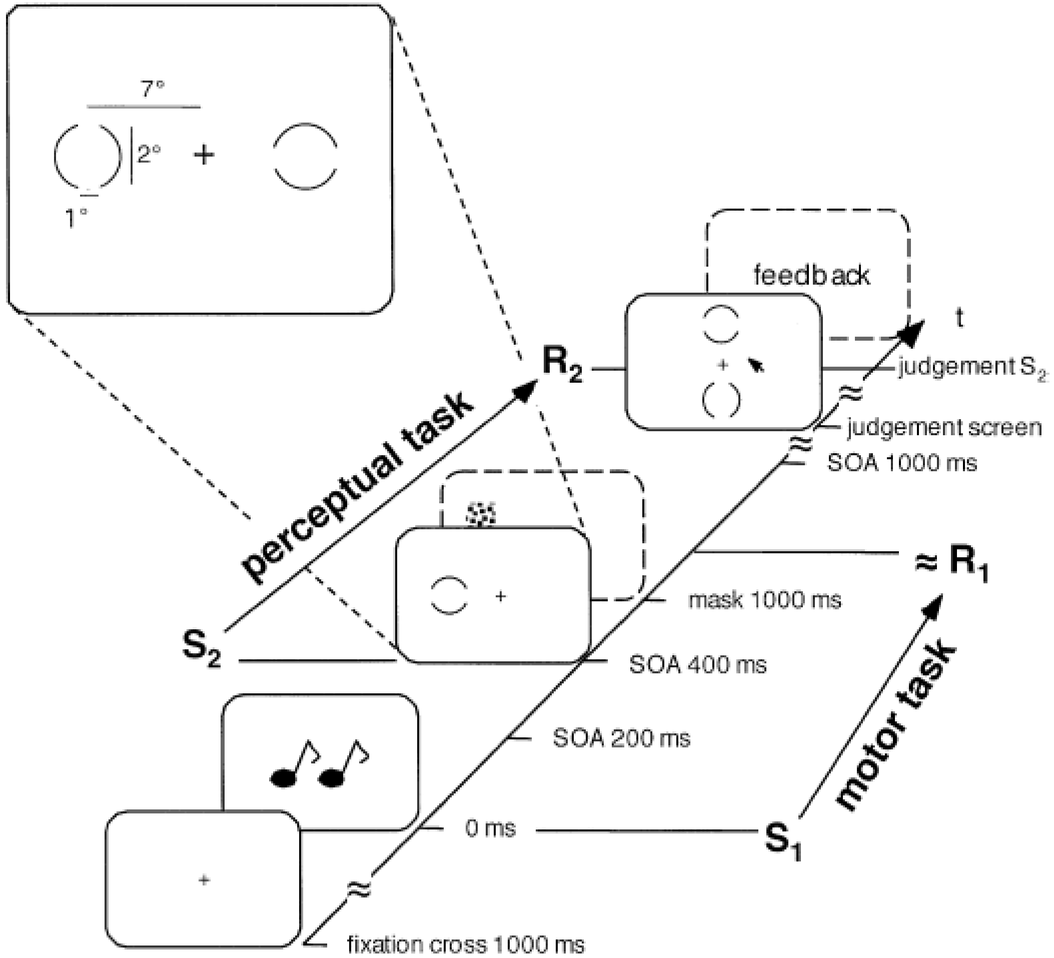

Figure 1. The sequence of events in the experiments. In the motor task, participants pressed a left or right key in response to tones as fast as possible. While doing this, a masked circle S2, in which a horizontally or vertically oriented gap was to be identified, appeared to the left or to the right of fixation with different SOAs (here 400 ms). The trial was completed with an unspeeded judgement of S2.

show up in Experiment 1? Note that we made some efforts to prevent deliberate processing of S2 location. Firstly, S2 location was irrelevant for the task at hand. Secondly, S2 did not require a speeded left–right response. Thirdly, especially at short SOAs, there should not be much capacity for processing S2 location because both the primary task and the secondary task were rather difficult. In particular, the primary task was expected to use limited-capacity processes that are also needed for encoding the relevant S2 feature (cf. Jolicoeur, 1999; Müsseler & Wühr, 2002). As a result, any processing capacity left over by the primary task should be devoted to processing the relevant S2 feature. If, however, the position of S2 would still affect the execution of R1 under these conditions, then this cross-task Simon effect might be taken as evidence for the automatic processing of S2 position.

Method

Participants. Thirteen participants (9 female, between 21 and 30 years of age, mean age 23.7 years) took part in the experiment, all with normal or corrected to normal vision. Most were students at University of Munich.

Apparatus, stimuli, and tasks. The experiments were run on an Apple Macintosh computer with Matlab using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). The stimuli were presented on a 17 inch colour monitor (75 Hz refresh rate, 1024 × 768 pixels). The participant's head was placed on a chin and forehead rest 500 mm in front of the monitor. The experiment was carried out in a dimly lit and sound-proof chamber.

Auditory stimuli (S1) were generated by square waves of 400 or 2000 Hz and were presented binaurally. A single tone lasted 50 ms, a two-tone sequence consisted of two 5 ms tones with an interstimulus interval of 40 ms. The mapping rules were as follows: A low single tone required a long key press ($\geq$250 ms) with the left-hand middle finger, while the low two-tone sequence required a short key press (< 250 ms) with the same finger. Correspondingly, a high single tone was mapped to a long key press with the right-hand middle finger and the high two-tone sequence was mapped to a short right-hand key press. These key presses (R1) were recorded with microswitches placed on a board in front of the subjects.

Visual stimuli (S2) were displayed in black-on-white projection and were presented 7° to the left or to the right of the screen centre. S2 were circles with a diameter of 2° of visual angle, in which either a horizontally or vertically arranged gap (1° of visual angle) was to be identified. S2 was displayed for an individually adjusted presentation time (see below) and then was replaced by a mask. The mask consisted of a square (subtending 3.6 × 3.6° of visual angle), in which each pixel was set white or black with equal probability.

Design. The experiment rested on a 2 × 3 design, with S2–R1 correspondence (corresponding vs. noncorresponding), and SOA between S1 and S2 (200, 400, or 1000 ms) as within-subjects factors. In each block, participants were confronted with each of the 48 combinations resulting from combining two S1 types (one or two tones), two S1 pitches (low or high), two S2 types (horizontally or vertically oriented gaps), two S2 positions (left or right), and three SOAs. Participants worked through 12 blocks of 48 trials. Dependent measures were RT1, the percentage of incorrect R1s, and the proportion of correctly identified S2.

Procedure. All trials started with the presentation of a fixation cross (Figure 1). After 1 s, the tone(s) occurred for 50 ms, which unequivocally signalled the required response R1. The instructions stressed the importance of responding quickly to the tone(s) and urged participants not to wait for S2 to appear before executing R1.

At an SOA of either 200, 400, or 1000 ms after S1, S2 was presented briefly to the left or to the right of the fixation cross and then replaced by the mask. A judgement screen with the visual stimuli one above the other appeared 2 s after the onset of the tones. Stimuli changed their relative positions in the judgement screen randomly from trial to trial. Participants had to indicate the identity of S2 by clicking on the corresponding stimulus with the computer mouse. An inter-trial interval of 1 s followed an error-free trial. An error feedback was given, if participants had made the wrong response to S1, if the corresponding reaction time exceeded 1000 ms and/or if participants reported the wrong S2.

To avoid ceiling or floor effects in the discrimination task, the presentation duration of S2 was adjusted every 10 trials to achieve 75% performance accuracy (i.e., 25% errors) across all SOA conditions. The presentation time was decreased by one screen refresh when the error rate was equal or lower than 15%. It was increased by one refresh when the error rate was equal or above 35%.

The experiment was preceded by a practice phase of half an hour, in which the S1–R1 mapping and the discrimination of S2 was practised. Additionally, in the practice phase the presentation duration of S2 was determined the first time. The experimental phase consisted of two sessions of 45 min each, which were performed on two subsequent days.

Results

S1–R1 task. Reaction times were calculated only for those trials in which none of the errors described above had occurred. RTs were entered into a 2 × 3 analysis of variance (ANOVA)[1] with S2–R1 correspondence (left/right R1 vs. left/right presentation of S2) and SOA (200, 400, and 1000 ms) as within-subjects variables. Across all conditions mean reaction time was 472 ms. A significant main effect of S2–R1 correspondence, $F(1, 12) = 5.25$, $p < .05$ (Figure 2), signalled the presence of a cross-task Simon effect. RT1 was shorter in corresponding than in noncorresponding conditions. Yet a significant interaction between S2–R1 correspondence and SOA, $F(2, 24) = 26.55$, $p < .001$, showed that the cross-task Simon effect was restricted to the shortest SOA of 200 ms ($D = 24$ ms).

RT effects were accompanied by similar effects in errors ($M = 8.2\%$). There were less errors in corresponding conditions than in noncorresponding conditions, $F(1, 12) = 25.45$, $p < .001$. Moreover, errors increased with decreasing SOA, $F(2, 24) = 6.24$, $p = .007$. Finally, the significant interaction between

[1] When necessary, F probabilities in the present and the following analyses were corrected according to Greenhouse-Geisser.

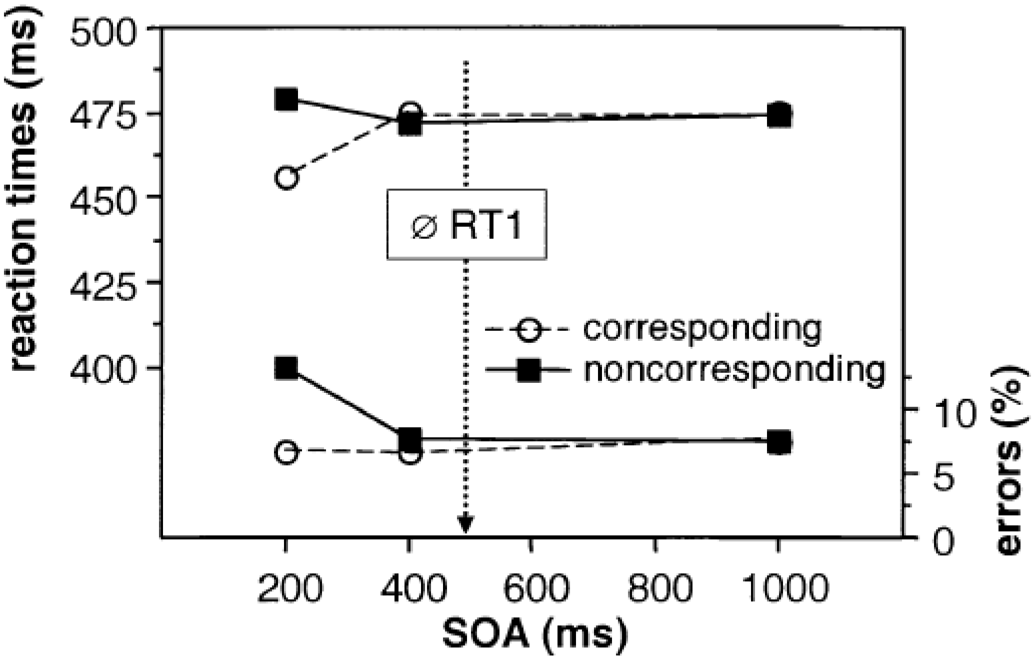

Figure 2. Mean reaction times and errors of the S1–R1 task in Experiment 1. Dashed and straight lines depict the corresponding and noncorresponding S2–R1 conditions, the *x*-axis depicts the SOAs between the presentation of S1 and S2. The dotted line indicated the mean reaction time of the first task (Ø RT1).

S2–R1 correspondence and SOA, $F(2, 24) = 9.24$, $p = .001$, indicated that the correspondence effect was again restricted to the shortest SOA (Figure 2).

S2–R2 task. The mean presentation duration for S2 across all participants was 47.2 ms. Across all conditions the mean error of identifying S2 was 23.3%. S2 identification errors were also subjected to a 2 (S2–R1 correspondence) × 3 (SOA) ANOVA. Errors decreased with increasing SOA, $F(2, 24) = 10.33$, $p = .001$ (Figure 3). Moreover, corresponding S2–R1 conditions produced somewhat higher discrimination performance than noncorresponding conditions, $F(1, 12) = 4.56$, $p = .054$. The interaction, however, was not significant, $F < 1$.

Discussion

Experiment 1 sought evidence for the automatic processing of irrelevant stimulus position. Participants were confronted with a difficult dual-task situation. In the primary task, participants responded to an auditory S1 with one of four speeded manual responses R1. Following S1 with a variable SOA, S2 was briefly presented and masked. Participants discriminated gaps in S2 and reported the orientation of an imaginary line through these gaps. S2 appeared randomly to the left or right of fixation, but S2 location was task irrelevant. The question was

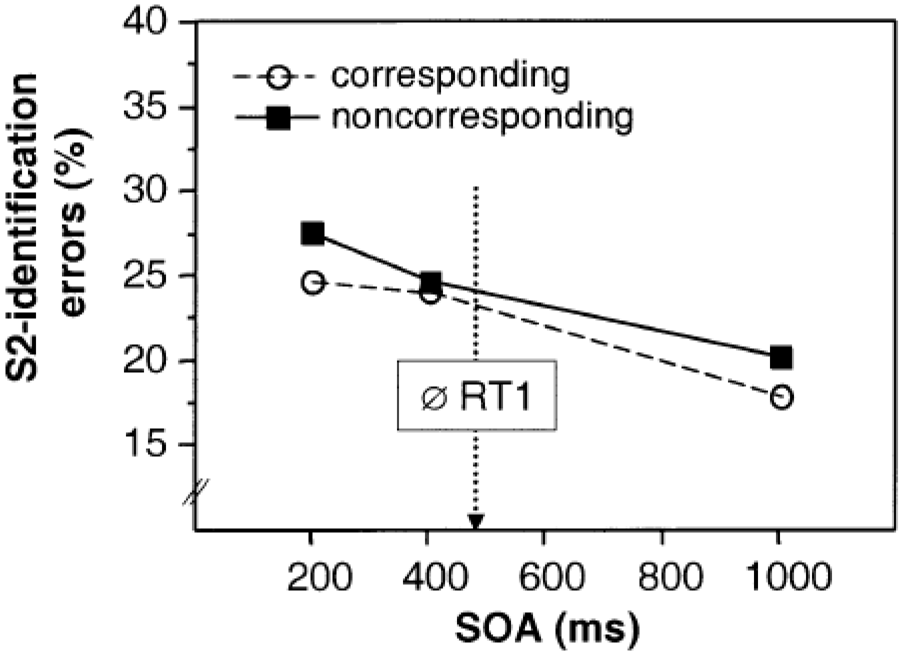

Figure 3. Mean error percentages of identifying S2 in Experiment 1. Dashed and straight lines depict the corresponding and noncorresponding S2–R1 conditions, the *x*-axis depicts the SOAs between the presentation of S1 and S2.

whether the spatial correspondence or noncorrespondence between S2 and R1 would affect the execution of R1.

Experiment 1 revealed two major findings. Firstly, discrimination performance for S2 decreased with decreasing SOA. When S2 appeared while R1 was still in preparation (SOA = 200 ms), discrimination performance was worse by 7.1%, compared to when S2 appeared after the execution of R1 (SOA = 1000 ms). We conclude that the manual response to S1 required limited-capacity processes that were also required for encoding the relevant S2 feature (Jolicoeur, 1999; Müsseler & Wühr, 2002). The transfer of quickly decaying stimulus information from sensory stores to short-term memory might be such a limited-capacity process (cf. Jolicoeur, 1999; Jolicoeur & Dell'Acqua, 1999). Moreover, we assume that any perceptual processing capacity that was not needed for S1 processing was devoted to process the relevant S2 feature, and not to the processing of S2 position.

The second major finding of Experiment 1 was the effect of irrelevant S2 position upon the execution of R1. Spatially corresponding S2 allowed for faster R1s than spatially noncorresponding S2s. This cross-task Simon effect was restricted to those cases, in which S2 appeared sufficiently long before R1 was executed (SOA = 200 ms; RT1 = 472 ms). For several reasons, the cross-task Simon effect can be attributed to automatic processing of S2 position. Firstly, the position of S2 was irrelevant for the task at hand, and participants had no incentive to deliberately process S2 position. Secondly, at least at short SOAs, there was little central capacity left for deliberately processing S2 position. Note that processing of the primary task did not leave enough capacity for an unimpaired processing of the relevant S2 feature. It is reasonable to assume that the amount of capacity, which was not needed for the primary-task, was devoted to process the relevant S2 feature, and not to process the irrelevant S2 position. In sum, Experiment 1 demonstrated a cross-task Simon effect that can be interpreted as evidence for the automatic processing of irrelevant stimulus position. Experiment 2 investigated the necessary conditions for the cross-task Simon effect to occur.

Before turning to Experiment 2, a third interesting finding of Experiment 1 should be mentioned. This result was the effect of S2–R1 correspondence on the efficiency of S2 encoding. The relevant S2 feature was discriminated more efficiently with spatially corresponding R1–S2 conditions than with non-corresponding conditions. This finding, which replicates the results of a previous study (Müsseler, Wühr, Danielmeier, & Zysset, 2005), is probably due to a shift of spatial attention towards the location of a to-be-performed action.

EXPERIMENT 2

Experiment 2 investigated the mechanisms that accomplished (automatic) encoding of S2 position in Experiment 1. Three mechanisms are conceivable. First, the abrupt onset of S2 in the empty visual display caused an exogenous (involuntary) shift of spatial attention towards the location of S2 (Jonides, 1981; Jonides & Yantis, 1988). This exogenous shift of attention established a spatial code for S2, and this spatial code affected the execution of R1 (exogenous-orienting hypothesis). Second, after the onset of S2 participants endogenously (voluntarily) shifted attention towards the location of S2. This endogenous shift of attention established a spatial code for S2, and this spatial code affected the execution of R1 (endogenous-orienting hypothesis; cf. Stoffer, 1991; Stoffer & Umiltà, 1997). Thirdly, the position of S2 is coded in relation to an object of reference, e.g., the fixation point, independently from shifting attention (referential-coding hypothesis; Hommel, 1993).

To investigate the mechanisms of the cross-task Simon effect, the dual-task procedure was used again. As in Experiment 1, the primary task was an auditory-manual four-choice response task. S2 followed S1 with a variable SOA. In the secondary task, participants identified a relevant feature of S2 and reported this feature without time constraints. Importantly, the horizontal position of S2 varied and, as a result, either corresponded with the horizontal position of R1 or not. Moreover, there was an additional manipulation in Experiment 2. In the S2-alone condition, S2 was presented to the left or right of fixation with the opposite location left empty (as in Experiment 1). In contrast, in the S2-with-distractor condition, S2 was accompanied by an irrelevant distractor stimulus that occurred at the horizontally opposite location.

Previous studies, in which an irrelevant stimulus was presented in addition to the imperative stimulus, have produced ambiguous results. For example, Hommel (1993) presented the target stimulus at one location and an uninformative stimulus at the alternative target location. Moreover, both possible target locations were surrounded with a large rectangle. In this situation, the attention-shifting account (Stoffer, 1991) assumes that attention zooms in from the rectangle to the targets' location, which should not produce a Simon effect. Yet, Hommel observed a Simon effect, and concluded that coding of the targets' position with reference to the irrelevant stimulus had produced the effect. However, in a subsequent study, Proctor and Lu (1994) consistently observed larger Simon effects when the target was accompanied by an uninformative distractor (at the opposite location) than when the target appeared alone. The authors interpreted their results as incompatible with the referential-coding account because ''inclusion of a noise stimulus in the location opposite the target should not affect the magnitude of the Simon effect when a fixation point is used, because the fixation already provides a referent for coding the target as left or right'' (p. 193). However, it is also possible that, if two objects of reference are available, then the more salient stimulus may serve as the referent. Moreover, it is also possible that the Simon effect increases with the salience of the reference stimulus.

The predictions for Experiment 2 were the following. If an exogenous attention shift had caused spatial coding of S2, then the cross-task Simon effect should only occur in the S2-alone condition of Experiment 2. In the S2-with-distractor condition, two abrupt onsets at different locations should attract attention in opposite directions, and the opposing forces might cancel each other out. If, however, an endogenous attention shift had caused spatial coding of S2 in Experiment 1, then the cross-task Simon effect might arise in both conditions. Finally, if the position of S2 was coded with respect to an object of reference, and not by attention shifts, then the cross-task Simon effect might also arise in both conditions. Moreover, according to our reasoning outlined above, a larger Simon effect might be expected in the S2-with-distractor condition.

A further procedural change in Experiment 2 should be mentioned. The presentation of an additional distractor stimulus could be expected to increase the difficulty of the task. Therefore, we decided to facilitate the discrimination of the relevant S2 feature by increasing presentation time and eliminating the mask from the procedure.

Method

Participants. Twenty-four observers participated in the experiment. Eleven participants (7 female, between 19 and 33 years of age, mean age 25.9 years) were randomly assigned to the S2-alone condition. Thirteen participants (10 female, between 19 and 32 years of age, mean age 23.5 years) were assigned to the S2-with-distractor condition.

Stimuli and procedure. Experiment 2 contained two conditions. The S2-alone condition was identical to Experiment 1. In contrast, in the S2-with-distractor condition, S2 was always accompanied by a distractor stimulus presented simultaneously in the contralateral visual field. The distractor was a full black circle of the same size as S2. Participants were instructed to ignore the distractor and to indicate the orientation of the gap in S2 at the end of a trial. In order to facilitate S2 discrimination, the mask was omitted from the procedure and the presentation duration of S2 was always 133 ms. Finally, the levels of the SOA factor were decreased to 100, 250, and 500 ms.

Design. The experiment rested on a 2 (S2–R1 correspondence) $\times$ 3 (SOA) $\times$ 2 (condition) mixed design. S2–R1 correspondence and SOA were within-subjects variables. Condition (S2 alone vs. S2 with distractor) was varied between participants, which were randomly assigned to both conditions. Each participant was confronted with 12 blocks consisting of 48 trials each.

Results

S1–R1 task. Across all conditions mean RT was 410 ms. RTs were entered into a 2 $\times$ 3 $\times$ 3 ANOVA. The main effects of SOA and condition were not significant. Yet the main effect of S2–R1 correspondence was significant, $F(1, 22) = 12.85$, $p < .01$, indicating a cross-task Simon effect (Figure 4). In fact, RT1 was shorter in corresponding than in noncorresponding conditions. Moreover, a significant interaction between S2–R1 correspondence and SOA, $F(2, 44) = 14.31$, $p < .001$, located the cross-task Simon effect at the shortest SOA. Importantly, however, the significant two-way interaction between correspondence and condition, $F(1, 22) = 9.11$, $p < .01$, indicated the presence of the cross-task Simon effect in the S2-alone condition ($D = 30$ ms), and its absence in the S2-with-distractor condition ($D = 6$ ms). Finally, the significant three-way interaction, $F(2, 44) = 4.90$, $p < .05$, showed that the cross-task Simon effect was restricted to the shortest SOA in the S2-alone condition.

RT effects were accompanied by corresponding effects in the errors of R1 ($M = 5.2\%$). The significant main effect of SOA, $F(2, 44) = 12.64$, $p < .001$, indicated an increase of errors with decreasing SOA. The significant main effect of S2–R1 correspondence, $F(1, 22) = 4.79$, $p < .05$, signalled a cross-task Simon effect. There were fewer errors with corresponding than with noncorresponding conditions. The main effect of condition was not significant. A significant two-way interaction between S2–R1 correspondence and SOA, $F(2, 44) = 7.00$, $p < .01$, located the cross-task Simon effect at the shortest SOA. However, the

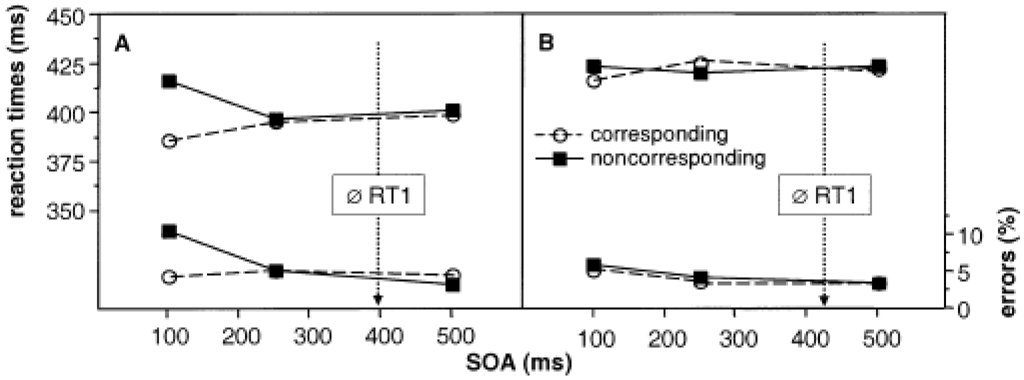

Figure 4. Mean reaction times and errors of the S1–R1 task in Experiment 2. Stimuli S2 were now unmasked and presented without (A) and with (B) an accompanying distractor in the contralateral visual field. Dashed and straight lines depict the corresponding and noncorresponding S2–R1 conditions, the *x*-axis depicts the SOAs between the presentation of S1 and S2.

significant three-way interaction, $F(2,44) = 5.29$, $p < .01$, made clear that the cross-task Simon effect exclusively arose at the shortest SOA in the S2-alone condition. At the 100 ms SOA, a Simon effect of 6.1% emerged in the S2-alone condition, but not in the S2-with-distractor condition ($D = 0.7\%$).

S2–R2 task. As expected by the easier S2–R2 task, discrimination of S2 was nearly perfect (mean S2-identification error = 1.7%). Therefore, error percentages were not analysed.

Discussion

Experiment 2 investigated the mechanisms underlying spatial S2 coding in Experiment 1, giving rise to the cross-task Simon effect. Participants again performed in a dual-task situation. In the S2-alone condition, S2 occurred alone either to the left or to the right of fixation. In the S2-with-distractor condition, however, S2 and an irrelevant distractor stimulus appeared simultaneously at opposite sides of fixation. Importantly, the cross-task Simon effect was restricted to the S2-alone condition. In this condition, at the short SOA, corresponding S2–R1 conditions produced shorter RT1s than spatially noncorresponding conditions. In contrast, no Simon effect at all occurred in the S2-with-distractor condition.

The results of Experiment 2 suggest that the cross-task Simon effect, observed in Experiment 1, was created by an exogenous shift of attention to the location of S2. In the S2-alone condition of Experiment 2, the singular abrupt onset of S2 most likely drew attention to the location of S2 in an automatic fashion. In contrast, in the S2-with-distractor condition of Experiment 2, there were two simultaneous onsets at opposing locations that both might have attracted attention and, as a result, might have cancelled each other out. Another possibility is that one of the two onsets captured attention with equal probability on each trial, thereby cancelling each other's effect out. In any case, we conclude that an exogenous shift of attention can create a spatial code for S2, which in turn can affect the production of R1. As an exogenous attention shift is assumed not to require processing capacity (cf. Jonides, 1981; Jonides & Yantis, 1988), this interpretation is still consistent with the idea that, at short SOAs, there was little capacity left for deliberately processing S2 position. In contrast, the absence of a cross-task Simon effect in the S2-with-distractor condition suggests that neither endogenous attention shifts nor referential coding of stimulus position produced the effect in Experiment 1. Both processes were equally possible in both conditions of Experiment 2.

The results of Experiment 2 are *not* evidence against the possibility that endogenous attention shifts or referential coding can also produce spatial stimulus codes. The problem is that we do not know whether endogenous attention shifts and/or referential coding occurred in the S2-with-distractor condition of Experiment 2 or not. We believe that at least endogenous attention shifts did not occur in Experiment 2 (and also not in Experiment 1) because it seems reasonable to assume that this mechanism needs limited processing, and there was probably little capacity left to process S2 position at the short SOAs. This interpretation is consistent with the results of previous studies that have observed Simon effects with simultaneous presentations of a target and a contralateral distractor (Hommel, 1993; Proctor & Lu, 1994). In these studies, in which only one stimulus had to be processed at a time, there was presumably enough processing capacity left over to perform endogenous attention shifts.

GENERAL DISCUSSION

Traditionally the processing of irrelevant position information in the Simon task has been considered an automatic process (e.g., Zhang et al., 1999). Recent research, however, called the traditional opinion into question (e.g., Ansorge & Wühr, 2004; Valle-Inclan & Redondo, 1998). The present study had two aims. The first aim was to put the hypothesis, according to which the processing of stimulus position in the Simon task was automatic, to a strong test. If the result of this test was positive, the second aim of this study was to investigate the possible mechanisms of automatic position coding in the Simon task.

Experiment 1 was aimed to provide a strong test of the hypothesis that encoding of stimulus position in the Simon task can proceed automatically. To do so, we tried to prevent voluntary processing of stimulus position. Clearly, the mere irrelevance of a stimulus feature does not warrant claiming that any effects of this feature upon behaviour were due to automatic processing. If, for example, a task is very simple, as it is usually the case in Simon experiments, then there may be enough capacity for voluntarily processing stimulus position, although it is irrelevant for the task at hand (cf. Lavie, 1995). Thus, in our experiments, we attempted to make processing of relevant information so demanding that there was no capacity left over for voluntarily processing the irrelevant position of a stimulus. To that aim, we used a dual-task procedure with an auditory-manual S1–R1 task and an S2-discrimination task with irrelevant stimulus locations.

Experiment 1 revealed two major results. Firstly, performing the primary task interfered with encoding S2. Thus, at short SOAs, processing in the primary task engaged limited-capacity processes, and these processes were not fully available for encoding the relevant S2 feature concurrently. It is reasonable to assume that the available amount of limited-capacity was completely used to process the relevant S2 feature, and was not used to process irrelevant S2 position. Secondly, a cross-task Simon effect was observed at short SOAs. That is, spatially corresponding S2–R1 conditions allowed for shorter RTs (and less errors) than spatially noncorresponding conditions. We attribute this effect to automatic processing of S2 position.

Experiment 2 investigated the possible mechanisms that gave rise to the cross-task Simon effect in Experiment 1. There were two different conditions with respect to the presentation of S2. The S2-alone condition was almost identical to Experiment 1. Yet, in the S2-with-distractor condition, a contralateral distractor stimulus was presented simultaneously with S2. The cross-task Simon effect occurred in the S2-alone condition, but not in the S2-with-distractor condition. These results support the exogenous-orienting hypothesis. A single abrupt onset, which could have attracted attention, only occurred in the S2-alone condition. In contrast, in the S2-with-distractor condition, two simultaneous onsets might have attracted attention to different locations and, as a result, these effects might have cancelled each other out.

In contrast to an exogenous attention shift, both endogenous attention shifts toward the location of the target stimulus, or referential coding of the targets' position, were equally possible in both conditions of Experiment 2. Thus, if one of these mechanisms had been responsible for the cross-task Simon effect in Experiment 1, the effect should have occurred in both conditions of Experiment 2. This, however, was not the case. Importantly, however, the results of our Experiment 2 do not suggest that endogenous attention shifts, or referential coding, cannot produce spatial stimulus codes that can give rise to Simon effects. It is more likely that these mechanisms were not active in our experiments. At least the endogenous attention shift needs processing capacity that was fully devoted to processing of the relevant information and therefore the cross-task Simon effect did not occur. Alternatively, it is also possible that—due to severe capacity limitations—these processes ran too slow in our experiments, and were therefore not able to affect R1 selection.

In sum, the results of the present study suggest that the Simon effect can arise from the automatic processing of stimulus position. Yet we have also described evidence taken to suggest that processing of spatial stimulus information in the

Simon task is not automatic (Valle-Inclan et al., 2002; Valle-Inclan & Redondo, 1998). The reason for this apparent discrepancy is that different tests of automatic processing in the Simon task have tested different criteria for automaticity: one criterion being the independence of automatic processes from capacity limitations, in other words, automatic processes do not require limited-capacity processes (e.g., attention, short-term consolidation); a second criterion being the unavoidability, that is, automatic processes are triggered whenever an appropriate stimulus is present, whether the observer intends to process that stimulus or not (cf. Brown et al., 2002; Jonides, 1981; Posner & Snyder, 1975). The present study showed that the formation of a spatial stimulus code can proceed without requiring limited-capacity processes. On the other hand, the study by Valle-Inclan and Redondo (1998) shows that processing stimulus position does not always interact with response selection. This interaction seems to depend upon the alternative responses being represented by spatial codes in working memory (cf. Ansorge & Wühr, 2004).

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