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Processing of irrelevant location information under dual-task conditions

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Abstract This study deals with the problem of whether the processing of irrelevant location information in Simon-like tasks is triggered exogenously or endogenously. In Experiment 1, the primary task required one to press, as fast as possible, a left-hand-side key or a right-hand-side key (R1) to the pitch of a tone that was presented binaurally (S1). The secondary task required identifying, without time constraints, a visual stimulus (S2) that appeared randomly to the left or right of screen center. Results showed that there was a correspondence (i.e., a cross-task Simon effect) between the location of R1 and the location of S2 when S2 was presented alone. The cross-task Simon effect became much smaller (and in-significant) when a noise stimulus was presented contralateral to S2. Experiment 2 was similar to Experiment 1, except that S2 appeared unpredictably in only one-third of the trials. Results of Experiment 2 closely replicated those of Experiment 1: the cross-task Simon effect was much greater when S2 was presented alone. Experiment 3 differed from Experiment 1 because S2 had to be processed in only one-third of the trials, in which its identity was to be reported. In the remaining two-thirds of the trials, participants could ignore S2. Results confirmed that the cross-task Simon effect was much greater when S2 was presented alone. In contrast, it did not matter whether S2 had to be processed or not. In conclusion, the present study supports the hypothesis that the task-irrelevant spatial code of the stimulus is formed automatically, likely through an exogenously triggered selection. The role of endogenously initiated selection, if any, is much less important.

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Processing of irrelevant location information under dual-task conditions

It has been known for some time that spatial relations between stimuli and responses can affect the performance of human participants even in situations in which stimulus position is irrelevant for the task at hand. This phenomenon is called the Simon effect (Hedge & Marsh, 1975). In a typical Simon task, for example, participants press a left-hand-side key to green stimuli and a right-hand-side key to red stimuli, while the stimuli appear to the left or right of the screen center. In this task, spatially corresponding conditions (i.e., a green left stimulus or a red right stimulus) produce faster responses and fewer errors than spatially non-corresponding conditions (i.e., a green right stimulus and a red left stimulus; e.g., Simon & Berbaum, 1990). The Simon effect hence demonstrates that participants process stimulus location even if it is task is irrelevant (see, e.g., Lu & Proctor, 1995, for a review).

Most accounts of the Simon effect assume that a spatial stimulus code is automatically formed for the irrelevant location of the imperative stimulus (e.g., Lu & Proctor, 1995; Umiltà & Nicoletti, 1990). Furthermore, it is assumed that the spatial stimulus code automatically activates a spatially corresponding response code (e.g., Hommel, 1997; Kornblum, Hasbroucq, & Osman, 1990; Zorzi & Umiltà, 1995). In spatially corresponding conditions, the stimulus location activates the correct response code and the required response is quickly executed. However, in spatially non-corresponding conditions, stimulus location activates a different response than that required by the relevant stimulus attribute and a response conflict arises. The response conflict increases the time needed to select the response (reaction times, RTs) and the probability of selecting a wrong response (error rate).

The present study deals with the question of whether the processing of irrelevant location information in Simon-like tasks occurs automatically or not. More precisely, the present experiments investigate whether the codings of location are initiated exogenously or endogenously. It is known that a sudden single stimulus onset in an otherwise empty visual field can exogenously attract attention towards the stimulus. However, it is also known that participants can initiate the selection of a stimulus endogenously, that is, by will (e.g., Jonides, 1981; Yantis & Jonides, 1990; Posner, Snyder, & Davidson, 1980; and review in Umiltà, 2000). But why should participants voluntarily shift attention towards the imperative stimulus in a Simon task? No doubt, attending to the location of the imperative stimulus improves encoding of the relevant stimulus attribute. Moreover, the typical Simon task imposes only little demands on processing capacity, leaving enough capacity for performing endogenous attention shifts towards the imperative stimulus.

The idea that endogenously initiated selections produce the spatial stimulus codes in the Simon task is supported by the results of a study by Proctor and Lu (1994). These authors tested predictions of the attention-shifting and the referential-coding account of location coding. An important manipulation in their study was to present the target stimulus (the letter H or S) either alone, to the left or to the right of the screen center, or to present it together with a contralateral noise stimulus (the letter Y). The interesting result was that contralateral presentation of the noise stimulus consistently increased the Simon effect as compared to when the target was presented alone. This result is difficult to explain for an account of location coding in terms of exogenously triggered attentions shifts. Presenting the target simultaneously with a contralateral noise stimulus should trigger attention shifts in opposite directions. The effects of such opposite attention shifts should cancel each other out. Yet the results of Proctor and Lu are consistent with an account of location coding in terms of endogenously initiated selections. Voluntary shifts of attention are possible both when the target is presented alone and when the target is presented with a contralateral noise stimulus. However, the voluntary initiation of an attention shift toward the target might be more difficult in the presence of the noise stimulus, thereby strengthening the spatial code of the target. Consequently, the size of the Simon effect should increase.

Given the wide acceptance of the idea that stimulus location in the Simon task is coded automatically, there is a surprising lack of studies testing this claim directly. A recent study by Müsseler, Koch, and Wühr (2005) provides an exception. These authors used a dual-task approach to investigate the hypothesis of automatic location coding in a Simon-like task. In their Experiment 1, participants made keypress responses (R1) with the left or the right hand to binaurally presented tones (S1). Simultaneously, participants had to identify a visual stimulus (S2) that randomly appeared to the left or right of screen center and that was masked after presentation. The dual task was used in order to tax the processing resources of the participants. This goal was achieved, as indicated by a marked dual-task interference. The question was whether a Simon effect would arise from a variation in spatial correspondence between S2 and R1, when resources for deliberately processing (irrelevant) S2 location were nearly exhausted. In fact, a cross-task Simon effect was obtained for stimulus-onset asynchronies (SOAs) smaller than the mean RT to S1 (see also Müsseler, Wühr, Danielmeier & Zysset, 2004). Yet this cross-task Simon effect could have been caused by either exogenous or endogenous shifts of attention towards the location of S2. To differentiate these possibilities, Müsseler et al. conducted a second experiment in which S2 was either presented alone or together with a contralateral noise stimulus (cf. Proctor & Lu, 1994). Importantly, a cross-task Simon effect was only observed when S2 appeared alone. Müsseler et al. interpreted these results as evidence for the claim that exogenous (i.e. automatically triggered) selections can produce Simon effects. If participants had enough resources for performing endogenous attention shifts towards the location of S2, such shifts (and, as a result, the Simon effect) should have occurred both in the S2-alone condition and in the S2-with-noise condition. In contrast, the fact that the Simon effect was absent in the latter condition suggests that the noise stimulus prevented an exogenous shift of attention towards the target location.

A particular interesting result of the Müsseler et al. (2005) study is their failure to obtain Simon effects with a contralateral noise stimulus, because this result conflicts with that of Proctor and Lu (1994). Apparently, a contralateral noise stimulus seems to increase Simon effects under single-task conditions, when capacity demands are low. In contrast, a contralateral noise stimulus seems to decrease (or even eliminate) the Simon effect under dual-task conditions, when capacity demands are high. This result suggests that multiple mechanisms might produce spatial stimulus codes in the Simon task. In particular, a single onset in the visual field might exogenously draw attention towards its location, thereby producing a spatial code and the Simon effect. If, however, there are two or more onsets in the visual field, attention might be endogenously shifted towards the location of the relevant stimulus, which requires processing capacity (cf. Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2005). The aim of the present study is to replicate and to extend this finding of Müsseler et al. (2005). Three dual-task experiments are reported, in which the participants performed left–right keypresses to tones and concurrently encoded a visual stimulus that appeared at a location to the left or a right. Importantly, in each experiment, the visual stimulus was either presented alone or together with a contralateral noise stimulus.

Experiment 1

The primary purpose of Experiment 1 was to replicate the findings of Experiment 2 of Müsseler et al. (2005). These authors investigated the processing of irrelevant location information under dual-task conditions. The primary task was to press a left-hand-side key or a right-hand-side key (R1) to the pitch of a tone (S1). The secondary task was to identify a visual stimulus (S2) that appeared randomly to the left or right of screen center. R1 had to be performed as quickly as possible after S1. In contrast, S2 was reported at the end of each trial without time constraints. Note that there is empirical evidence that a speeded manual discrimination, such as the one that must be performed to rightly execute R1, is slowed down when participants are also asked to later perform an unspeeded discrimination (Umiltà, Nicoletti, Simion, Tagliabue, & Bagnara, 1992). In other words, it is reasonable to assume that having to identify a visual stimulus afterwards affects the capacity available to execute R1.

In Experiment 2 of Müsseler et al. (2005), the SOA between S1 and S2 was randomly varied. Moreover, S2 was either presented alone or simultaneously with a contralateral noise stimulus. A cross-task Simon effect at short SOAs (i.e. for SOAs smaller than RT1) was found when S2 appeared alone. Yet no Simon effect occurred when S2 was presented together with a contralateral noise stimulus. These results conflict with those obtained by Proctor and Lu (1994), who observed larger Simon effects with contralateral noise stimuli than when the target was presented alone. Experiment 1 aimed at replicating the results of Müsseler et al. (2005, Experiment 2) with a similar dual-task procedure. Yet the SOAs used in the present experiments were somewhat different from those used in the previous study. In particular, the present experiment included a 0-ms SOA condition, which should maximize temporal overlap between processing in the two tasks.

Method

Apparatus and stimuli

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″ color monitor (75 Hz refresh rate, 1,024 × 768 pix). The participant's head was placed on a chin rest, 500 mm in front of the monitor. The experiment was carried out in a dimly lit and soundproof chamber.

Auditory stimuli (S1) were generated by square waves of 400 or 2,000 Hz and were presented binaurally for 50 ms. For half the participants, the low tone required a keypress with the right-hand middle finger, and the high tone, a keypress with the left-hand middle finger. For the other half, this mapping was reversed. The keypresses (R1) were recorded with microswitches placed on a board in front of the participant.

Visual stimuli (S2) were displayed in black-on-white projection and were presented 7° to the left or to the right of the screen center. 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. The noise stimulus was a circle with no gap. S2 and the noise stimulus were displayed for 133 ms.

Design

The experiment had a 2 × 2 × 3 design with condition (S2 alone vs. S2 with the noise stimulus), S2–R1 correspondence (corresponding vs. non-corresponding), and SOA between S1 and S2 (0, 200, or 750 ms) as within-subjects factors. The condition was presented in blocks, with the sequence of blocks balanced between participants. In each block, participants were confronted with each of the 192 combinations resulting from combining two S1 pitches (low or high), two S2 types (horizontally or vertically oriented gaps), two S2 positions (left or right), three SOAs and eight repetitions. Dependent measures were RT1 and the percentage of incorrect R1s, but the proportion of rightly identified S2 was also analyzed.

Procedure

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

At an SOA of either 0, 200, or 750 ms after S1, S2 was briefly presented to the left or to the right of the fixation cross. A judgment screen with the visual stimuli to the left and to the right at the bottom of the screen appeared 2 s after the onset of the tone. Stimuli changed their relative positions in the judgment screen randomly from trial to trial, thus observers could not prepare the judgment response in advance. The identity of S2 was indicated by pressing the key, which corresponded to perceived S2.

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 RT for R1 exceeded 1,000 ms, and/or if participants reported the wrong S2. The experiment was preceded by a practice phase of 10 min, in which the S1–R1 mapping and the discrimination of S2 was practiced. The experimental phase lasted about 75 min.

Participants

Twelve observers between 21 and 36 years of age (7 female) were paid to participate in the experiment. Data

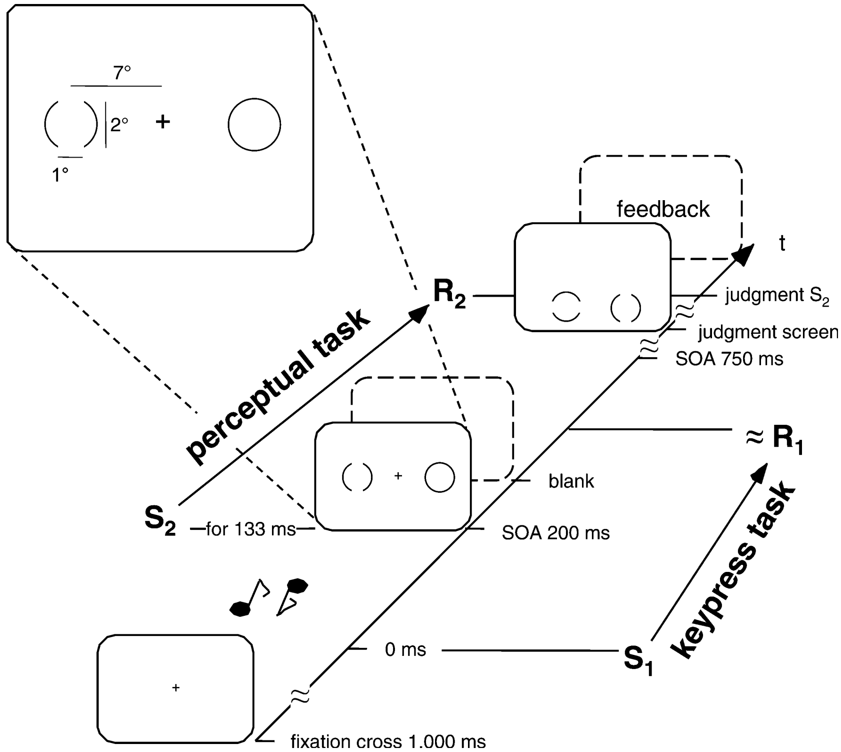


Fig. 1 The sequence of events in Experiment 1. In the keypress task, participants pressed a left or right key in response to tones as fast as possible. While doing this, a *circle* S2, in which a horizontally or vertically oriented gap (here *vertically*) was to be identified, appeared to the left or to the right of fixation (*here left*) with different SOAs (here 200 ms). S2 was presented alone or together with an irrelevant noise stimulus in the contralateral visual field (*a full circle*, here in the *right* visual field). The trial was completed with an unspeeded judgment of S2 in the judgment screen. In this screen stimuli changed their relative positions randomly from trial to trial, thus observers could not prepare the judgment response in advance. The identity of S2 was indicated by pressing the key, which corresponded to the perceived S2 (here *right*)

pertaining to one participant were excluded because his/her error percentage for identifying S2 was 25.2%, while the mean was only 1.3% for the remaining participants.

Results

Discrimination of S2 was nearly perfect (98.7% correct). RTs for the S1–R1 task were calculated only for those trials in which none of the errors described above had occurred. RT1s and errors were entered into separate 2 (S2 alone vs.S2 with the noise stimulus) × 2 (left/right R1 vs. left/right presentation of S2) × 3 (SOAs) repeated measures analyses of variance (ANOVAs). Across all conditions, mean RT1 was 333 ms and the mean error percentage was 3.7%. Figure 2 shows that an effect of S2–R1 correspondence was mainly observed in RTs of the S2-alone condition at the 0-ms SOA. The three-way interaction was significant in the RT ANOVA, $F(2, 20) = 5.25$, $MSe = 227.96$, $P < 0.05$, but not in the error ANOVA, $F(2, 20) = 1.46$, n.s.

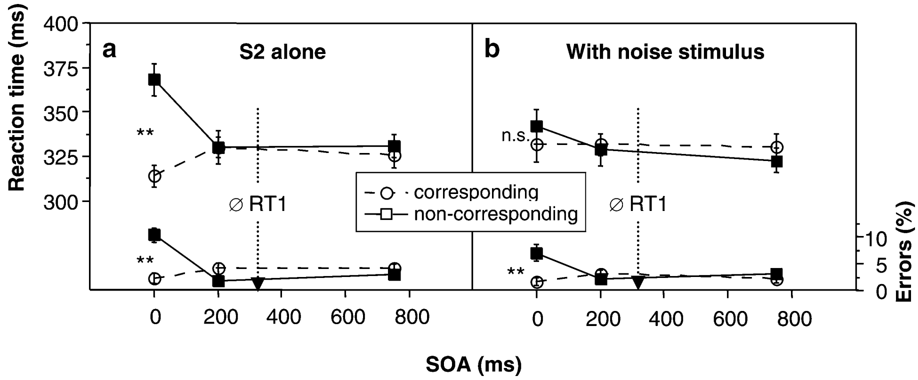
Additionally, there were significant main effects of SOA, signaling a decrease of RT1s (and errors) with an increase of SOA from 339 ms (5.3% errors at 0-ms SOA) to 330 ms (2.9%, 200-ms SOA) and 328 ms (3.0%, 750-ms SOA), $F(2, 20) = 6.77$, $MSe = 238{,}79$, $P < 0.01$ with RT1s and $F(2, 20) = 9.41$, $MSe = 9.18$, $P < 0.01$ with errors. The main effect of S2-R1 correspondence was significant in RT1s and errors, $F(1, 10) = 24.12$, $MSe = 127.19$, $P < 0.01$ and $F(1, 10) = 13.98$, $MSe = 6.48$, $P < 0.01$. The two-way interaction of correspondence and SOA, $F(2, 20) = 13.82$, $MSe = 301.91$, $P < 0.001$ and $F(2, 20) = 25.50$, $MSe = 8.37$, $P < 0.001$, was significant too for both RT1 and errors. The interaction of condition and correspondence was only significant for RT1s, with $F(1, 10) = 23.94$, $MSe = 142.90$, $P < 0.01$, but not for errors.

Separate *t*-tests between corresponding and non-corresponding S2–R1 RTs at the 0-ms SOA showed a significant difference in the S2-alone condition [314 vs. 368 ms, $t(10) = -4.41$, $P < 0.01$], but not in the noise condition [332 vs. 342 ms, $t(10) = -1.62$, $P > 0.10$]. Thus, the results showed a cross-task Simon effect of 54 ms (non-corresponding minus corresponding RT1s) in the S2-alone condition and a clearly reduced and insignificant 10-ms difference in the noise condition. However, corresponding *t*-tests of the errors revealed significant effects of both the S2-alone and the noise condition [2.3 vs. 10.2%, $t(10) = -4.41$, $P < 0.01$ and 1.7 vs. 7.1%, $t(10) = -3.54$, $P < 0.01$].

Discussion

Experiment 1 investigated the processing of irrelevant location information under dual-task conditions. The primary task was to press the left-hand-side or right-hand-side key in response to a tone. The secondary task was to investigate a visual stimulus that followed with a variable SOA to the tone and appeared randomly to the left or right of the screen center. The variation of spatial correspondence between the visual S2 and the manual R1 produced a cross-task Simon effect at the short SOA, when S2 was presented alone. In contrast, in the RT

Fig. 2 Mean reaction times and percentage errors (with standard errors of the mean between participants) in the S2-alone (*left*) and with-noise (*right*) condition of Experiment 1. *Dashed* and *straight lines* depict the corresponding and non-corresponding S2–R1 relationships, the *x*-axis depicts the SOAs between the presentation of S1 and S2. The *dotted line* indicated the mean reaction time (Ø RT1)



analysis a cross-task Simon effect did not occur when S2 was accompanied by a contralateral noise stimulus, but in the error analysis it occurred. Nevertheless, the results of the present basically replicate the results of Experiment 2 of Müsseler et al. (2005). In particular, the difference between the S2-alone and the S2-with-noise conditions supports the notion that an exogenously (i.e. automatically) triggered shift of attention towards S2 produces a spatial code for that stimulus, which in turn elicits a Simon effect.

Given the high capacity demands of the dual-task situation, it is unlikely that participants deliberately coded the irrelevant location of S2 independently from the relevant S2 attribute. Hence, processing of S2 location was simply a by-product of processing the relevant S2 attribute. Since both exogenous and endogenous shifts of attention would aid in processing the relevant S2 attribute, either one might have occurred and produced a spatial stimulus code for S2. Yet, endogenous selections should have been possible both when S2 appeared alone and when S2 was accompanied by the contralateral noise stimulus. In contrast, exogenous shifts of attention towards the location of S2 should have occurred only when S2 appeared alone. Hence the pattern of results suggests two conclusions. The first is that exogenous attention shifts produced the Simon effects in the S2-alone condition. The second is that endogenous attention shifts were most likely prevented by the high capacity demands of the dual-task situation in Experiment 1 (cf. Jolicœur et al., 2005).

The fact that the Simon effect occurred only with the 0-ms SOA can be explained with reference to the so-called accessory stimulus version of the Simon task. In it, typically, an accessory lateral stimulus (e.g. a sound unrelated to the task) accompanies the task-relevant stimulus, which, in itself, conveys no spatial information: RTs are faster when the location of the irrelevant stimulus corresponds with the location of the response (e.g., Acosta & Simon, 1976; Hommel, 1995; Notebaert & Soetens, 2003). It is possible that, in the present experiment, the 0-ms SOA produced a condition similar to the one that characterizes the accessory stimulus, whereas, when the SOA was longer, the response to the tone had already been selected when S2 was presented. Therefore, response selection was not affected by location of S2 (e.g., Rubichi, Nicoletti, Iani, & Umiltà, 1997).

It is theoretically possible that presenting a contralateral noise stimulus eliminated the Simon effect because attention was randomly drawn to the location of S2 or to the location of the noise stimulus, and not because the noise stimulus prevented exogenous attention shifts. Yet random attention shifts should decrease identification performance in the S2-with-noise condition compared with the S2-alone condition. This was not the case. Therefore, in our view, the present results are more in line with the conclusion that presenting the noise stimulus prevented exogenously driven selections and that a lack of processing capacity prevented endogenously driven selections. The following experiments further investigate the conditions under which the irrelevant location of a stimulus is encoded under dual-task conditions.

Experiment 2

Experiment 2 further investigates the nature of the mechanisms that are able to produce a spatial stimulus code. It used the same dual-task procedure as Experiment 1, that is, S2 either appeared alone or together with a contralateral noise stimulus. The important difference with respect to Experiment 1 was that, in Experiment 2, S2 appeared unpredictably in only one-third of the trials. The less frequent occurrence of S2 might decrease the preparedness to execute endogenous attention shifts towards the location of S2 and, thus, might lead to smaller Simon effects than in Experiment 1. Such a result might indicate that participants do have some control over the kind of attention shifts that produce the Simon effect in the S2-alone condition. The alternative is that the less frequent occurrence of S2 might also increase the saliency of S2 and, hence, lead to stronger exogenous attention shifts toward S2 location. This in turn might produce even larger Simon effects than in Experiment 1. Because a cross-task Simon effect was only observed for the 0-ms SOA in Experiment 1, S1 and S2 were always presented simultaneously in Experiment 2.

Method

Stimuli, procedure, and design

These were the same as in Experiment 1, except for the following changes. Auditory stimuli (S1) and visual stimuli (S2) were always presented simultaneously (an SOA of 0 ms). Additionally, S2 was presented unpredictably in only one-third of the trials. Thus, the experiment was characterized by a 2 (condition: S2 alone vs. S2 with the noise stimulus) × 2 (S2–R1 correspondence) within-subjects design. Again, the condition was blocked with the sequence of blocks balanced between participants. Within each block, participants went through 144 trials, but, as only one-third of them were analyzable, the subsequent analysis was based on 48 measurements per participant per cell. The experiment lasted about 50 min.

Participants

Twelve observers (9 female) between 20 and 28 years of age participated in the experiment.

Results and discussion

Again, discrimination of S2 was nearly perfect with 97.4% correct. Across all conditions, mean RT1 was 389 ms and mean error percentage was 7.9%. RT1s and errors were entered into 2 × 2 ANOVAs. The ANOVA on RT1s revealed a main effect of correspondence, that is, RT1s were faster with S2–R1 correspondence than with non-correspondence, $F(1, 11) = 41.55$, $MSe = 520.48$, $P < 0.001$. More importantly, the interaction was significant with $F(1, 11) = 45.85$, $MSe = 199.65$, $P < 0.001$ (cf. Fig. 3). In the S2-alone condition, the cross-task Simon effect was 70 ms, $t(11) = -7.87$, $P < 0.001$, while it was only 15 ms with the noise stimulus. However, even this latter difference was significant with $t(11) = -2.32$, $P < 0.05$. The error analysis revealed only a main effect with fewer errors in corresponding pairing than in non-corresponding S2–R1 ones pairings (2.8 vs. 13.0%, $F(1, 11) = 35.10$, $MSe = 35.87$, $P < 0.001$).

Experiment 2 investigated the processing of irrelevant location information, as garnered by Simon effects between S2 and R1, when only S2 was presented in one third of the trials. When S2 was presented, then it either appeared alone or together with a contralateral noise stimulus. The results of Experiment 2 were almost identical to those of Experiment 1, in which S2 had appeared on each trial. In Experiment 2, when S2 appeared alone, there was a large Simon effect of 70 ms, which was numerically larger then the 54-ms Simon effect observed in Experiment 1. Yet, this difference was not statistically reliable. When S2 was accompanied by a contralateral noise stimulus, there was only a very weak Simon effect. However, in Experiment 2, the Simon effect in the S2-with-noise condition, although numerically small, was statistically significant, whereas it was not so in Experiment 1.

Experiment 3

Experiment 3 further investigated the degree of automaticity with which attention shifts towards the location of the visual stimulus are triggered in our task. S2 was again presented on every trial but it had to be processed on only one-third of the trials, in which the relevant feature had to be reported. In the remaining two-thirds of the trials, participants could completely ignore S2. Importantly, at the beginning of each trial, a visual cue informed the participants about whether S2 was to be processed or not. The question was whether the spatial correspondence between the position of a to-be-processed S2 and the position of R1 would have the same effects as the spatial correspondence between a to-be-ignored S2 and the position of R1. In particular, if the participants are not able to shift attention endogenously towards the location of S2, then relevant S2 and irrelevant S2 should produce identical results: Relevant and irrelevant S2 should produce similar-sized Simon effects in the S2-alone condition. Moreover, neither relevant nor irrelevant S2 should produce Simon effects in the S2-with-noise condition. In contrast, if the participants are able to select endogenously the location of S2, then the Simon effects for relevant S2 and for irrelevant S2 should be different. That is, relevant S2 should produce larger Simon effects than irrelevant S2 in the S2-alone condition. Similarly, relevant S2 should produce Simon effects in the S2-with-noise condition, whereas irrelevant S2 should not.

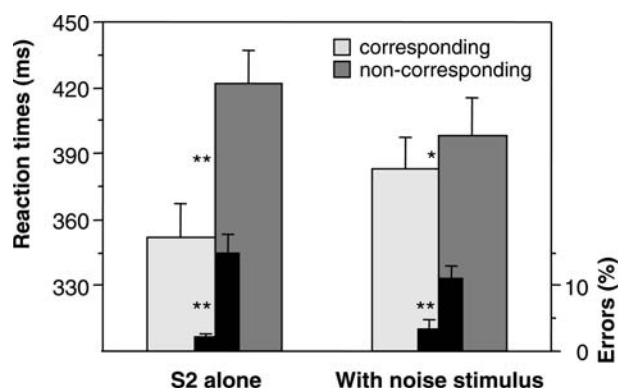


Fig. 3 Mean reaction times and percentage errors in the S2-alone (*left*) and with-noise (*right*) condition of Experiment 2. Stimuli S2 were now presented always simultaneously and in only one-third of the trials. *Light* and *dark bars* depict the corresponding and non-corresponding S2-R1 relationships

Method

Stimuli, procedure, and design

These were the same as in Experiment 2, except for the following changes. S2 was task-relevant in only one-third of the trials. The sequence of events on S2-relevant trials was as in the previous experiments. This means that at the beginning of a trial, a black fixation cross appeared 1 s before S2 presentation and that at the end of a trial the judgment screen was presented (cf. Fig. 1).

In contrast, an S2-irrelevant trial was signaled by the presentation of a red-colored fixation cross 1 s before S2 presentation. Consequently, in these trials observers could ignore S2 presentation in advance. Additionally, on these trials, S2 stimuli were red colored and the judgment screen was omitted.

Participants

Eleven observers (9 female) between 19 and 32 years of age participated in the experiment.

Results

Observers were able to discriminate S2 rightly on 98.1% of the trials. Across all conditions mean RT1 was 353 ms and mean error percentage was 4.2%. RT1s and errors were entered into 2 (S2 relevance) × 2 (condition: S2 alone vs. S2 with the noise stimulus) × 2 (S2–R1 correspondence) ANOVAs. As in the previous experiments, the interaction of condition and correspondence was significant in the ANOVA for RTs with $F(1, 10) = 64.34$, $MSe = 263.42$, $P < 0.001$ (Fig. 4). In other words, S2–R1 correspondence effects were again much smaller in the S2-with-noise conditions than in the S2-alone conditions. Additionally, the interaction between S2 relevance and S2–R1 correspondence was significant, with $F(1, 10) = 6.07$, $MSe = 133.31$, $P < 0.05$. This means that the S2–R1 correspondence effects were larger in the S2-relevant trials than in the S2-irrelevant ones. The main effect of the condition revealed that RT1s were somewhat slower in the S2-alone than in the S2-with-noise condition [367 vs. 339 ms, $F(1, 10) = 6.06$, $MSe = 2736.07$, $P < 0.05$]. As in the previous experiment, the main effect of S2–R1 correspondence was to signal shorter RT1s in corresponding trials than in non-corresponding ones [335 vs. 370 ms, $F(1, 10) = 85.06$, $MSe = 325.24$, $P < 0.001$]. A similar effect showed up for errors (1.9 vs. 6.5%, $F(1, 10) = 12.13$, $MSe = 36.70$, $P < 0.01$).

Separate *t*-tests between corresponding and non-corresponding S2–R1 RTs and errors showed significant differences in the S2-alone condition, irrespectively of whether S2 was relevant or not. The cross-task Simon effect was 72 ms for RTs of the S2-relevant trials [334 vs. 406 ms, $t(10) = -9.35$, $P < 0.001$] and 6.4% for errors [2.3 vs. 8.7%, $t(10) = -3.56$, $P < 0.01$]. In the S2-irrelevant trials, the effect decreased to 54 ms for RTs [336 vs. 390 ms, $t(10) = -6.47$, $P < 0.001$] and 5.3% for errors [1.1 vs. 6.4%, $t(10) = -2.90$, $P < 0.05$]. When S2 is presented alone without the contralateral noise, the cross-task Simon effect seems always to occur.

In contrast, with contralateral noise and S2 relevant, the cross-task Simon effect was only 11 ms, although it was statistically significant [334 vs. 345 ms, $t(10) = -2.36$, $P < 0.05$] and 4.2% [2.3 vs. 6.4%, $t(10) = -2.47$, $P < 0.05$]. It disappeared in the S2-irrelevant trials. The residual effects of 4 ms for RTs and 2.1% for errors were not significant ($P > 0.10$, at least).

Discussion

Experiment 3 compared the effects of two factors on the processing of irrelevant location information, as indicated by the Simon effects of spatial S–R correspondence between the position of a visual stimulus S2 and the position of a manual response R1. The first factor was the presentation of S2 alone or together with a contralateral noise stimulus. The second factor was the relevance of S2, that is, whether S2 had to be processed or could be ignored. The results were quite clear. The presentation of S2 alone or the presentation of S2 with a contralateral noise stimulus had a large effect on the size of the Simon effect. A target stimulus presented alone produced a large Simon effect (72 and 54 ms). Presenting the target together with a contralateral noise stimulus almost eliminated the Simon effect (11 and 4 ms). In contrast, whether S2 had to be processed or not had only a small impact on the Simon effect. In fact, in the omnibus ANOVA all sources involving the factor "S2 relevance" were insignificant (i.e., all $F < 1$). However, a relevant S2 produced numerically larger Simon effects than an irrelevant S2. This numerical increase produced a significant Simon effect of 11 ms for relevant S2 stimuli that were accompanied by a contralateral noise stimulus.

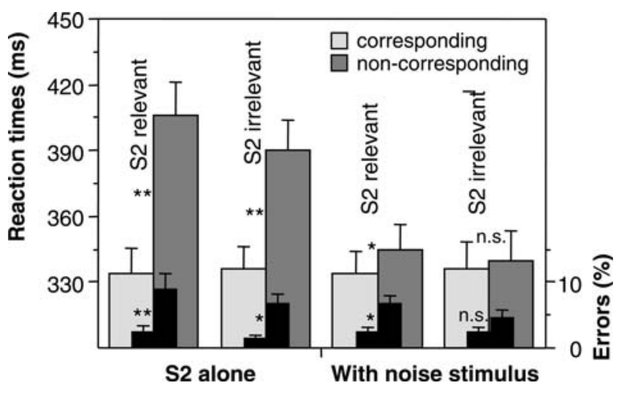


Fig. 4 Mean reaction times and percentage errors in the S2-alone (*left*) and with-noise (*right*) condition of Experiment 2. Stimuli S2 were now pre-experimentally declared as task relevant and irrelevant. *Light* and *dark bars* depict the corresponding and non-corresponding S2–R1 relationships

This result suggests, as did a similar result in Experiment 2, that participants can sometimes perform endogenous attention shifts towards the location of S2 under the dual-task conditions of our experiments. However, much more impressive is the huge Simon effect of 54 ms that occurred although participants could ignore S2 completely. In sum, the results of Experiment 3 suggest that the coding of S2 location is in most parts achieved by exogenous shifts of attention towards S2.

General discussion

The present study was concerned with the problem of whether the processing of irrelevant location information in a Simon-like task is triggered exogenously or endogenously. The primary task required pressing, as fast as possible, the left-hand-side key or the right-hand-side key (R1) to the pitch of a tone that was presented binaurally (S1). The secondary task required identifying, without time constraints, a visual stimulus (S2), which appeared randomly to the left or right of screen center. Figure 5 gives an overview of the net correspondence effects (the difference of non-corresponding and corresponding RTs and errors, respectively) observed in the experiments. Large correspondence effects between location of R1 and location of S2 were observed in all experiments when S2 was presented alone. These effects became much smaller (and sometimes non-significant) when a noise stimulus was presented contralateral to S2. This let us conclude that the task-irrelevant spatial code of the stimulus is formed automatically, likely through an exogenously triggered attention shift. The role of endogenously initiated selection is, if any, much less important.

According to Jonides (1981; also see Umiltà, 2000) there are three empirical criteria of automaticity. The first criterion is capacity (or load sensitivity). If formation of the spatial stimulus code, being automatic, does not require processing resources, it should not be affected by a secondary task. Apparently, this criterion of automaticity is fulfilled because the Simon effect, which signals the formation of the spatial stimulus code, manifested itself in every experiment, in spite of the presence of a resource-consuming secondary task. Moreover, the size of the Simon effect was not smaller than the size of the Simon effect that is found when only one task has to be performed (e.g., Lu & Proctor, 1995; Stoffer & Umiltà, 1997 for reviews).

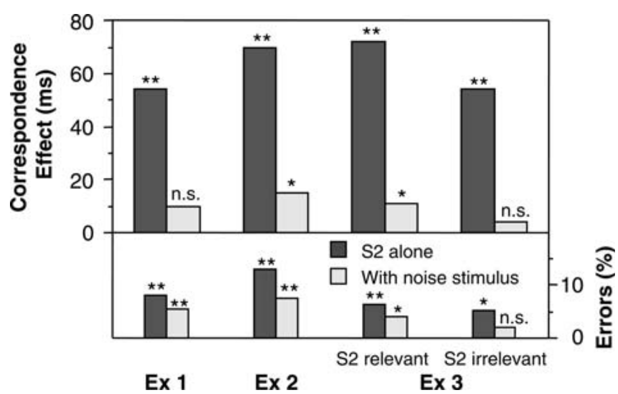


Fig. 5 Overview of the correspondence effects (the difference of non-corresponding and corresponding S2–R1 reaction times and errors, respectively) in the experiments. For comparability, only the 0-ms SOA of Experiment 1 is depicted

The second criterion is resistance to suppression. The degree to which a particular process can be suppressed provides an indication of its level of automaticity. In Experiment 3 here, participants received advance information that should have rendered it easy to suppress formation of the spatial stimulus code. However, formation of the spatial stimulus code was not suppressed, as attested by the fact that the Simon effect was present. This fulfills the criterion of resistance to suppression.

The third criterion is expectancy. If a process is automatic, it should not be affected by the observer's expectations. In Experiment 2 here, S2 appeared in only one-third of the trials. In spite of this, the Simon effect was present and was of the usual magnitude. This attests to the fact that the spatial stimulus code was formed even though the participant's expectations of being presented with a lateralized stimulus were low. This fulfills the third criterion.

In sum, the three criteria can be invoked as evidence in favor of the fact that attention was automatically captured to the location of S2, rather than being intentionally directed there. Additional evidence is that, in every experiment, the Simon effect manifested itself only when S2 was presented alone. The strong decrease, or even the lack, of the Simon effect when the noise stimulus is presented can easily be explained by proposing that two opposite automatic shifts cancel each other out. One shift would be triggered by S2, whereas the other would be triggered by the noise stimulus. In contrast, if the selection towards S2 were initiated voluntarily, the correspondence effect should not suffer much if a noise stimulus was presented on the other side. In fact, the voluntary shift to S2 should eventually prevail over the automatic shift to the noise stimulus (e.g., Umiltà, 2000).

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