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Multiple spatial codes and temporal overlap in choice-reaction tasks

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Abstract Experiments by Umiltà and Liotti (1987) and Lamberts, Tavernier, & d'Ydewalle (1992) examined the Simon effect (an influence of irrelevant stimulus location on reaction time) as a function of multiple frames of reference. The Simon effect was absent for all reference frames in the former experiment, leading Stoffer (1991) to propose that a spatial code is formed only if the last step in directing attention to the imperative stimulus is a lateral shift. However, the Simon effect was evident for all frames in the latter experiment. Hommel (1994) proposed that the multiple spatial codes implied by Lamberts et al.'s findings were also activated in Umiltà and Liotti's experiment but had decayed by the time the relevant stimulus information had been identified. Experiments 1, 2, and 3 examined these accounts of attention shifting, multiple codes, and temporal overlap for variations of the Simon task in which the stimulus could occur in one of either eight or four possible stimulus locations. Three stimulus sets that differed in ease of discriminability were used in each experiment. Experiments 1 and 2 were replications and extensions of those of Lamberts et al. and Umiltà and Liotti, respectively. In both experiments, two boxes, with a stimulus inside of one, appeared simultaneously, and the subject was to respond to the identity of the stimulus. Experiment 3 used a procedure in which the four stimulus locations were demarcated by three vertical lines. Two of the three experiments showed Simon effects with respect to multiple frames of reference, and the magnitude of these effects was a decreasing function of the difficulty of stimulus discriminability. Spatial compatibility proper was examined in Experiment 4 using the same layout as Experiment 3. In this case, only the relevant frame of reference was coded. On the whole, the results indicate that multiple codes are formed, but not automatically, and that those codes decay when irrelevant.

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Introduction

Fitts and his co-workers introduced the concept of stimulus-response (S-R) compatibility, which is that the reaction time (RT) to a stimulus depends on the relation between the stimulus and the response sets (Fitts & Deininger, 1954; Fitts & Seeger, 1953). In regards to spatial compatibility, RTs are shorter when there is correspondence between the spatial position of the stimulus and the spatial position of the response than when there is not. For example, when a left or right keypress is made to a stimulus in a left or right location, the RT will be significantly faster when the left response is assigned to the left stimulus and the right response to the right stimulus than when the assignment is reversed (e.g., Proctor & Dutta, 1993).

The effect of spatial S-R compatibility is also observed when the stimulus location is irrelevant for selecting the response; this effect of irrelevant information is known as the Simon effect (see Lu & Proctor, 1995, and Simon, 1990, for reviews). In the Simon task, a non-location attribute of the stimulus, such as its shape, determines whether a left or right response is to be made. Although the spatial position of the stimulus is irrelevant, RTs are faster when the location of the stimulus corresponds with that of the response than when it does not (e.g., Simon & Rudell, 1967; Stoffer, 1991; Umiltà & Liotti, 1987; Umiltà & Nicoletti, 1985; Wallace, 1971, 1972). The Simon effect is presumed to reflect competition from activation of the response code corresponding to the irrelevant stimulus location code (e.g., De Jong, Liang, & Lauber, 1994; Zorzi & Umiltà, 1995).

Because the Simon effect occurs in many situations, exceptions are of considerable theoretical interest. Umiltà and Liotti (1987) in their Experiment 3 conducted a task variation in which no Simon effect occurred. The experiment was a two-choice task in which a pair of boxes was presented either to the left or right side of a central fixation cross, as shown in Fig. 1. The imperative stimulus was a square or a rectangle that appeared inside one of the boxes, either simultaneous with the box onsets or after a 500-ms delay. The relative position (left or right) of the stimulus with respect to the two boxes varied randomly from trial to trial. The geometrical shape of the imperative stimulus determined which response, a left or right keypress, was to be made. The results showed a significant interaction between delay, stimulus relative position (left or right box), and response. A Simon effect with regard to relative position of 21 ms occurred when stimulus onset was delayed relative to that of the boxes, but only a nonsignificant effect of 2 ms was evident when the stimulus and boxes were presented simultaneously. Umiltà and Liotti noted the apparent importance of the failure to obtain the Simon effect in the no-delay condition, but did not provide a satisfactory explanation of this outcome.

A plausible explanation for the absence of the Simon effect under conditions of simultaneous presentation in Umiltà and Liotti's (1987) experiment was proposed by Stoffer (1991). He conducted an experiment similar to Umiltà and Liotti's, with the primary difference being that he also included a condition in which the possible stimulus locations were contained within a large rectangular frame presented to the left or right of fixation (see Fig. 2). Stoffer's results for his small-cue condition, in which the two pertinent stimulus locations were each surrounded by a square box, replicated those of Umiltà and Liotti. The Simon effect was apparent when the onset of the stimulus was delayed relative to that of the boxes, but not when the onsets were simultaneous. In the large-cue condition, in which the two pertinent stimulus locations were designated by a single rectangle that surrounded both, the Simon effect was not evident even when stimulus onset was delayed. Stoffer postulated an attention-shifting account of the Simon effect to explain his results and those of Umiltà and Liotti. According to this account, attention must be focused on the imperative stimulus before a response to it can be selected. The fundamental idea of this account is that a spatial code will be created, and the Simon effect observed, only if the last step in the focusing of attention onto the stimulus is a lateral shift. If the last step involves what Stoffer called attentional zooming, that is, shifting from a higher level of organization (e.g., the reference frame) to a lower level (e.g., the imperative stimulus), then the stimulus will not be coded as left or right and a Simon effect will not occur. Stoffer proposed this to be the case for the large-cue condition regardless of delay and the small-cue condition when there is no delay.

Although Umiltà and Liotti (1987) and Stoffer (1991) found no evidence of a Simon effect as a function of either relative position or hemispace when the possible stimulus locations were indicated by a pair of boxes that appeared simultaneously with the stimulus, Lamberts, Tavernier, & d' Ydewalle (1992) found Simon effects with respect to both frames of reference, as well as a third reference frame, in a similar experiment (see Fig. 3). The main difference in their method was that eight possible stimulus locations were used, rather than four. At the start of each trial, a fixation cross was presented in the middle of the left half or right half of the screen, instead of in the center of the screen. From that point onward, the trials were like the no delay condition of Umiltà and Liotti. Five-hundred ms after the fixation cross appeared in the left or right hemispace, two boxes – one of which contained the imperative stimulus, a circle or a square – occurred either to the left or right of the fixation cross. Thus, Lamberts et al.'s experiment differed from those of Umiltà and Liotti and of Stoffer in having three frames of reference, arising from divisions of hemispace, hemifield, and relative position (see Fig. 4), rather than just two frames of reference. In contrast to the results obtained by Umiltà and Liotti and by Stoffer, Lamberts et al. found Simon effects as a function of all the frames of reference, which they interpreted as indicating that

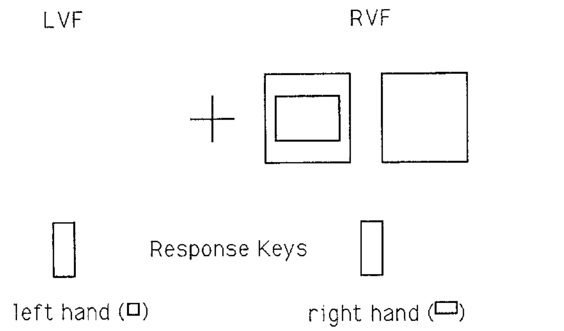

Fig. 1 Schematic diagram of the display condition of Umiltà and Liotti's (1987) Experiment 3 that led to the disappearance of the Simon effect (LVF = Left Visual Field, RVF = Right Visual Field)

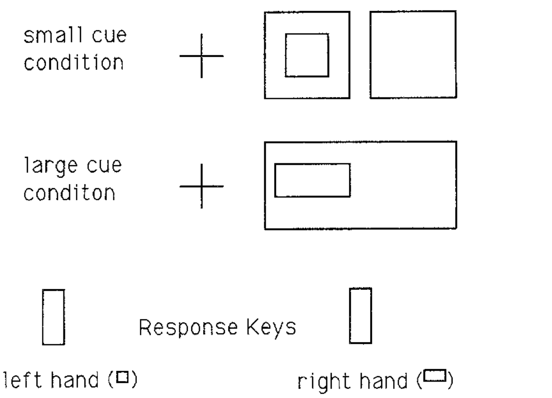

Fig. 2 Schematic diagram of the display conditions of Stoffer (1991) that also led to the disappearance of the Simon effect

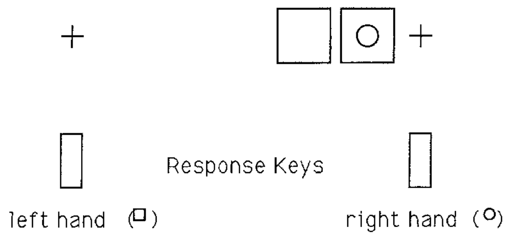

Fig. 3 Schematic diagram of the display condition of Lamberts et al.'s (1992) Experiment 2 that found a Simon effect. (Note: Only one fixation cross appears at a time)

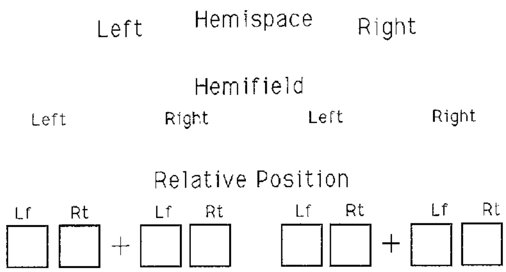

Fig. 4 The eight locations in which the stimulus could occur in Exp. 1, resulting from the orthogonal manipulation of hemispace, hemifield, and relative position (Lf = left and Rt = right)

multiple spatial codes are generated automatically. Stoffer's attention-shifting account would seem to predict no Simon effects in Lamberts et al.'s task because hemispace is cued, thus allowing attention to be shifted to the appropriate hemispace before stimulus presentation, and then the remainder of the trial is like the simultaneous condition of Umiltà and Liotti, for which the attention-shifting account posits that no location code is created.

Hommel (1994) noted this discrepancy between the two sets of findings and hypothesized that it was due to the different stimulus sets used (rectangle/square for Umiltà & Liotti, 1987, and Stoffer, 1991; circle/square for Lamberts et al., 1992). Contrary to the attention-shifting account, he proposed that spatial codes are formed with respect to multiple frames of reference, as Lamberts et al.'s findings suggested, but that they decay if identification of the relevant stimulus information is delayed. Because the rectangle/square discrimination should be more difficult than the circle/square discrimination, the spatial codes may have been sufficiently strong to affect performance at the time that response selection occurred in Lamberts et al.'s study, but not in the studies of Umiltà and Liotti and of Stoffer. To test this temporal overlap hypothesis, Hommel replicated Umiltà and Liotti's Experiment 3 using two different stimulus sets, the rectangle/square set used by Umiltà and Liotti and by Stoffer and a red/green color set. The fact that the two colors are relatively distinct should allow a stimulus from the color set to be identified faster than a stimulus from the form set.

The results of Hommel's (1994) experiment indicated that responses were indeed faster in the color condition than in the form condition. More importantly, a significant interaction of stimulus side and response, indicative of a Simon effect based on hemispace, occurred for the color condition but not for the form condition. Because the stimulus identification was more difficult for the square/rectangle set than for the red/green set, thereby taking longer, Hommel concluded that the spatial code for hemispace had decayed to the point where it no longer influenced the response code by the time that the stimulus form was identified. It should be noted that the absence of a Simon effect based on relative position for the red/green set is not predicted by the hypothesis that multiple spatial codes are automatically formed and then decay.

Hommel's (1994) effort at a resolution of the discrepant results obtained in the studies that have investigated the possibility of spatial coding with respect to multiple frames of reference suggests a role for temporal overlap in accounting for the discrepancies. However, there remain methodological differences and inconsistencies of results across the previous experiments that preclude an unambiguous conclusion that the results can be explained entirely in terms of the decay of multiple spatial codes. First, whether Hommel's results obtained with the four-stimulus layout of Umiltà and Liotti (1987) can be generalized to the eight-stimulus layout of Lamberts et al. (1992) is unknown. Second, the circle/square stimulus set used by Lamberts et al. was not used in Hommel's replication of Umiltà and Liotti's experiment and has never been compared directly to the rectangle/square stimulus set used by them. Third, the red/green stimulus set used by Hommel produced a pattern of results (a Simon effect with respect to hemispace but not to relative position) that is not completely consistent with either of the results obtained in the other studies or with either of the alternative theoretical accounts. Consequently, the existing studies do not allow for a determination of whether temporal overlap of multiple codes is capable of accounting for all of the patterns of results or whether there is also a role for attention shifting.

Experiment 1 of our study is a replication of Lamberts et al.'s (1992) experiment, and Experiment 2 is a replication of Umiltà and Liotti's (1987) experiment using all three sets of stimuli – red/green, circle/square, and rectangle/square – that were employed in various combinations or singly in the aforementioned studies. The results were analyzed and compared in terms of a Simon effect for the divisions based on hemispace and relative position for both experiments, and the additional division of hemifield for the Lamberts et al. replication. These steps were taken to provide a more complete and consistent comparison across experiments and stimulus sets, thus allowing a more thorough evaluation of the alternative theoretical accounts.

Experiment 3 was conducted to determine if similar results would occur within a Simon task using the same stimulus sets, but with a unique visual layout in which four possible stimulus locations were demarcated by three vertical lines that appeared prior to the onset of the stimulus. Because it is rare for the Simon effect to be absent, as is the case using Umiltà and Liotti's (1987) procedure, we thought it important to determine whether similar results could be obtained when the stimulus was not enclosed in a box. Experiment 4 was similar to Experiment 3, but the response was based on whether the stimulus was located to the left or right of the center line (i.e., the experiment examined S-R compatibility proper). This experiment was conducted to determine if the spatial coding would be restricted to only the relevant reference frame, as in Umiltà and Liotti's study.

Experiment 1

This experiment was a replication of Lamberts et al.'s (1992) Experiment 2 using their circle/square stimulus set, Umiltà and Liotti's (1987) rectangle/square set, and Hommel's (1994) red/green set. The procedure was as follows. First, a lateral fixation point was randomly presented at either the left or the right side of the visual display. The fixation point served as a cue indicating the hemispace of stimulus presentation. As such, the subjects were certain about the hemispace of stimulus presentation at the time the stimulus appeared. In the second stage of each trial, two square boxes appeared simultaneously to either the left or right of the fixation point (both boxes appeared simultaneously). One of these boxes contained the imperative stimulus, to which a left or right keypress was to be made. Stimulus location was irrelevant to the task, and the experimental situation was paradigmatic of the Simon effect.

The eight locations in which the stimulus could occur are presented in Fig. 4. Those positions resulted from an orthogonal manipulation of three factors: hemispace of stimulus presentation, visual hemifield within hemispace, and relative position within hemifield. Thus, the effects of correspondence of stimulus location and response location with respect to the three frames of reference can be examined. Based on the results of Lamberts et al. (1992), we would expect to obtain Simon effects for all three reference frames. Such results would be consistent with the view that spatial codes are formed automatically upon presentation of the stimulus and not with Stoffer's (1991) attention-shifting model. If Hommel's (1994) temporal overlap hypothesis is correct, the magnitudes of the Simon effects for all reference frames should decrease as discrimination difficulty increases, that is, from the red/green to circle/square to rectangle/square sets. Moreover, within each stimulus condition, the effect magnitude should decrease as RT increases.

Method

Subjects. Seventy-two students enrolled in Introductory Psychology courses at Purdue University participated in the experiment to fulfill a class requirement. The subjects had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Apparatus and stimuli. The experiment was conducted in a dimly lit room. An IBM-compatible microcomputer was used for stimulus generation, response registration, and timing, which were controlled by Micro Experimental Laboratory. The subjects sat directly in front of a 14-in. (36-cm) color CRT at a viewing distance of approximately 55 cm. The CRT was 30 cm in width and 20 cm in height. The stimuli were a 5 × 5-mm (corresponding to .52° × .52° of visual angle) fixation cross, presented in either the left or right hemispace, pairs of 20 × 20-mm (2.08° × 2.08°) outline boxes that were separated by a 5-mm (.52°) gap between their inner edges, and three sets of imperative stimuli. These sets were (a) red and green circles 10 mm (1.04°) in diameter; (b) a square 9 mm (.94°) and a circle 10 mm (1.04°) in diameter; and (c) a square 9 mm (.94°) and a rectangle 10 mm (1.04°) in length and 8 mm (.83°) in width. The fixation cross could appear 60 mm (6.23°) to the left or right of the center of the display. The two boxes appeared to the left or right of the fixation cross, with the separation between the fixation cross and the inner edge of the closest box being 7 mm (.73°). The imperative stimulus was always presented in the geometrical center of one of the boxes. The response keys were the "z" and "/" keys, which are located at the extreme positions on the bottom row of the computer keyboard. The keys were 160 mm apart and operated by the left and right index fingers, respectively.

Procedure. For each trial, the timing of the sequence of events was as follows. First, the fixation cross was presented either to the left or right of center to designate the hemispace in which the stimulus would occur; it remained present for 500 ms. At the offset of the cross, two boxes were shown, both to the left or both to the right of the fixated location. One of these boxes contained the imperative stimulus. The boxes and stimulus remained present until a response was made. The intertrial interval was 1 s, and it was initiated immediately if the response was correct or after a 400-Hz tone sounded for 500 ms if the response was incorrect.

Subjects were instructed to respond as fast and as accurately as possible. They were told that a cross would appear on the left or right side of the screen and that at its offset two boxes, one of which contained the stimulus to which they were to respond, would appear to the left or right of the cross's location. No mention was made regarding eye movements. The S-R mappings were described in terms of the shapes or colors of the alternative stimuli and the positions of the assigned responses. All subjects performed with only one set of stimuli. Twenty-four subjects were randomly assigned to each stimulus set. For each stimulus set, half the subjects were instructed to press the left key to one of the stimuli and the right key to the other, and half of the subjects received the reverse S-R mapping. Each subject took part in one experimental session that consisted of 64 practice trials and 320 test trials. The test trials were comprised of 20 trials for each stimulus in each of the eight locations, with the order randomized.

Results

The percent of incorrect responses was 3.55. RTs for incorrect responses were excluded from the analysis. For each subject, the mean RTs and error percentages (EPs) were calculated as a function of hemispace (left, right), hemifield (left, right), relative position (left, right),

Table 1 Experiment 1: Mean reaction times in milliseconds and error percentages (in parentheses) as a function of stimulus type, hemispace, hemifield, relative position, and response

Stimulus type	Left hemispace		Right hemispace	
	Left hemi-field	Right hemi-field	Left hemi-field	Right hemi-field
Red/green				
Left relative position				
Left response	427 (2.8)	438 (4.5)	433 (1.6)	452 (4.2)
Right response	457 (5.4)	426 (3.5)	442 (5.6)	421 (2.8)
Right relative position				
Left response	431 (3.5)	463 (6.0)	440 (3.8)	472 (5.7)
Right response	447 (4.2)	417 (2.6)	419 (3.5)	417 (2.8)
Circle/square				
Left relative position				
Left response	478 (2.4)	467 (2.1)	479 (2.4)	478 (2.3)
Right response	501 (3.9)	464 (3.7)	499 (5.0)	457 (2.3)
Right relative position				
Left response	474 (2.4)	500 (6.3)	478 (3.3)	497 (5.6)
Right response	469 (3.7)	459 (2.4)	457 (2.1)	469 (3.0)
Rectangle/square				
Left relative position				
Left response	625 (4.3)	565 (2.4)	601 (1.7)	581 (2.4)
Right response	638 (7.5)	559 (1.6)	611 (2.8)	561 (3.0)
Right relative position				
Left response	577 (3.3)	621 (3.5)	569 (4.3)	630 (5.8)
Right response	584 (3.1)	600 (3.1)	550 (3.0)	621 (3.5)

stimulus type (red/green, circle/square, rectangle/square), and response (left, right). The results are summarized in Table 1.

Mean reaction times. An analysis of variance (ANOVA) of the RT data showed significant main effects of stimulus type, $F(2, 69) = 54.56$, $p = .0001$, $MSE = 46{,}229$, and response location, $F(1, 69) = 13.61$, $p = .0004$, $MSE = 1{,}943$. Responses to the red/green stimuli ($M = 438$ ms) were faster than those to the circle/square stimuli ($M = 477$ ms), which were faster than those to the rectangle/square stimuli ($M = 593$ ms), and the right response ($M = 498$ ms) was faster than the left response ($M = 507$ ms). The interaction between relative position and hemifield was significant, $F(1, 69) = 198.22$, $p = .0001$, $MSE = 884$, as was the interaction between hemispace and hemifield, $F(1, 69) = 29.83$, $p = .0001$, $MSE = 739$. Both of these interactions are a consequence of stimuli closer to fixation being responded to faster than those further away. The three-way interaction of hemispace × hemifield × stimulus type was also significant, $F(2, 69) = 7.81$, $p = .0009$, $MSE = 739$, with the difference between the inner and outer positions being larger for the difficult rectangle/square discrimination than for the easier circle/square and red/green discriminations.

Of most concern are the interactions involving response, since these are indicative of the Simon effect. The interaction of hemifield and response was significant, $F(1, 69) = 69.99$, $p = .0001$, $MSE = 898$, indicating a Simon effect with respect to hemifield of 15 ms. Hemifield and response also entered into a three-way interaction with stimulus type, $F(2, 69) = 5.42$, $p = .0065$, $MSE = 898$, with the size of the Simon effect of hemifield decreasing from the red/green set to circle/square set to the rectangle/square set (Ms = 22, 14, and 9 ms), respectively. However, individual analyses for each stimulus set showed the hemifield × response interaction to be significant in all three cases: red/green, $F(1, 23) = 82.22$, $p = .0001$, $MSE = 581$; circle/square, $F(1, 23) = 13.62$, $p = .0012$, $MSE = 1344$; and rectangle/square, $F(1, 23) = 8.38$, $p = .0082$, $MSE = 767$.

Relative position also interacted with response, $F(1, 69) = 34.94$, $p = .0001$, $MSE = 937$, with a Simon effect of 11 ms obtained. Although the three-way interaction of these variables with stimulus type was not significant, individual analyses showed the Simon effect to be significant for the red/green set, $F(1, 23) = 22.76$, $p = .0001$, $MSE = 696$, and circle/square set, $F(1, 23) = 16.44$, $p = .0005$, $MSE = 1{,}180$, but not for the rectangle/square set, $F(1, 23) = 2.49$, $p = .1282$, $MSE = 935$. The mean Simon effects were 14, 14, and 5 ms, respectively, for the red/green, circle/square, and rectangle/square sets.

A Simon effect of 6 ms with respect to hemispace was obtained as well, as indicated by a significant interaction of hemispace and response, $F(1, 69) = 13.22$, $p = .0005$, $MSE = 784$. The three-way interaction of these variables with stimulus set was not significant, but the individual analyses showed a significant effect for the red/green stimulus set, $F(1, 23) = 28.33$, $p = .0001$, $MSE = 420$, but not for the circle/square set, $F(1, 23) = 2.88$, $p = .1030$, $MSE = 330$, or the rectangle /square set, $F(1, 23) = 0.83$, $p = .3723$, $MSE = 1601$. The Simon effect was 12, 3, and 4 ms, respectively, for the red/green, circle/square, and rectangle/square sets.

As a result of having Simon effects as a function of all three frames of reference, the eight positions showed a decreasing correspondence effect as the position cues moved from all the same to increasingly different (e.g., left relative position, left hemispace, and left hemifield to left relative position, left hemispace, and right hemifield). The four-way interaction of hemispace, hemifield, and relative position with response was significant, $F(1, 69) = 12.97$, $p = .0006$, $MSE = 561$, indicating that the differences in RT for the left and right response across the eight stimulus locations were not entirely additive functions of the Simon effects for the three frames of reference.

Error percentage. The only significant main effect for the EP data was relative position, $F(1, 69) = 4.47$, $p = .0380$, $MSE = .0012$, with errors to stimuli in the right relative position (EP = 3.8%) slightly outnumbering those to stimuli in the left relative position

(EP = 3.4%). The two-way interactions of relative position with hemispace and with hemifield were significant, $Fs(1, 69) = 4.27$ and 9.97, $ps = .0426$ and $.0024$, $MSEs = .0012$ and $.0022$. Stimuli closer to fixation were responded to more accurately than those further away. The three-way interaction of relative position and hemispace with stimulus type was also significant, $F(2, 69) = 3.41$, $p = .0388$, $MSE = .0012$, as was that of hemispace and hemifield with stimulus type, $F(2, 69) = 4.10$, $p = .0207$, $MSE = .0016$. As with RT, position of the stimulus with respect to the center of the screen was more important for the difficult rectangle/square discrimination than for the less difficult discriminations of circle/square and red/green.

The interaction of hemifield × response was significant, $F(1, 69) = 16.00$, $p = .0002$, $MSE = .0029$, as was the interaction of relative position × response, $F(1, 69) = 16.08$, $p = .0002$, $MSE = .0029$. These terms reflect Simon effects as a function of hemifield and relative position in the error data.

Reaction time distributions. RT distributions for each subject were computed for the leftmost and rightmost stimulus locations as a function of response position and stimulus type. We examined these stimulus locations because all three spatial codes are in agreement and either correspond or do not correspond with the response location. An analysis of the distributions similar to that of De Jong et al. (1994) was performed. These distributions were divided into 20% bins, and mean RTs were determined for each bin. For each bin, mean RTs for the corresponding S-R positions were subtracted from those for the noncorresponding positions. These difference scores, averaged across subjects, are shown in Fig. 5. Two of the three stimulus types, the form conditions of circle/square and rectangle/square, showed decreasing Simon effects as RT increased, consistent with the decay assumption of the temporal overlap model. However, the red/green color set showed no tendency for the Simon effect to decrease with increasing RTs.

Discussion

The results we obtained with the circle/square stimulus set used by Lamberts et al. (1992) are similar to their findings. For this stimulus set, the RT data showed significant Simon effects as a function of hemifield and relative position, with a nonsignificant tendency toward a small Simon effect for hemispace. The hemispace effect was significant in Lamberts et al.'s study, but the magnitude of the mean difference was small, as in our study. Moreover, when averaged across the three stimulus types, significant Simon effects were evident for all three frames of reference in our experiment, providing additional confirmation that stimulus location was coded with respect to multiple reference frames. According to the multiple codes hypothesis, as the spatial codes from different spatial cues vary from being in complete agreement (e.g., all indicate "left") to conflicting (e.g., one code indicates "left " and two codes indicate "right"), the Simon effect will decrease in magnitude or disappear entirely. The present experiment clearly demonstrated this pattern of results.

The color stimuli were identified faster than the form stimuli, and the more distinct circle/square set was identified faster than the rectangle/square set. This

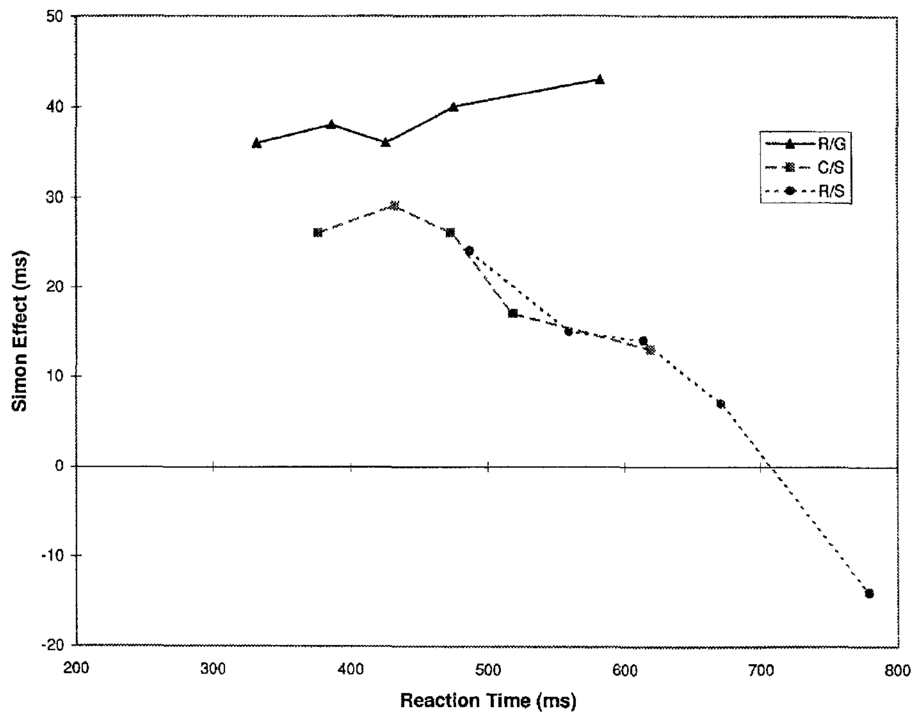

Fig. 5 The Simon effect for the red/green (R/G), circle/square (C/S), and rectangle/square (R/S) stimulus sets in Experiment 1 as a function of 20% RT bins

ordering is as expected and allows for the predictions of Hommel's (1994) temporal overlap hypothesis to be evaluated. The red/green stimulus set, for which RTs were fastest, yielded the largest Simon effects, whereas the rectangle/square stimulus set, for which RTs were slowest, yielded the smallest effects (averaged across hemispace, hemifield, and response location, the mean Simon effects were 16, 10, and 6 ms for the red/green, circle/square, and rectangle/square sets, respectively). This ordering of effect sizes is as predicted by the temporal overlap hypothesis.

The findings from Experiment 1 are consistent with the results of Lamberts et al.'s (1992) Experiment 2, in which a Simon effect for relative position was found for the circle/square set, and are also consistent with Umiltà and Liotti's (1987) Experiment 3, in which no Simon effect for relative position was found for the rectangle/square set, and with Hommel's (1994) finding of a Simon effect for hemispace with the color stimuli. Distributional analyses for the RTs with the respective stimulus sets showed the predicted decrease in magnitude of the Simon effect as RT increased for the circle/square and rectangle/square conditions, but not for the red/green condition. Thus, with the exception of the distributional analysis for the red/green set, the results are in agreement with the hypotheses that stimulus location is automatically coded relative to all three reference frames and that the strengths of these codes decrease across time.

Experiment 2

This experiment was a replication of the no-delay condition in Umiltà and Liotti's (1987) Experiment 3 that used four possible stimulus locations. The present experiment was conducted to examine the data in terms of Simon effects for both relative position and hemispace for all three stimulus sets. The four locations in which the stimulus could occur are presented in Fig. 6. The positions resulted from the orthogonal manipulation of two factors, hemispace (stimulus side) and relative position within the hemispace.

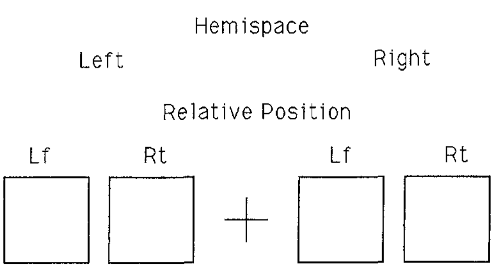

Fig. 6 The four locations in which the stimulus could occur in Experiment 2 resulting from the orthogonal manipulation of hemispace and relative position (Lf = left and Rt = right)

The experimental procedure was as follows. First, a fixation point was presented in the middle of the visual display. In the second stage of each trial, two square boxes appeared simultaneously to either the left or right of the fixation point. The geometrical shape or color of the stimulus determined which response, a left or right keypress, was to be made. If stimulus location is coded automatically and the location codes decay, Simon effects should be obtained for both reference frames and should decrease in magnitude both between and within stimulus sets as responding is slowed.

Method

Subjects. Twenty-four students from the same pool as in Experiment 1 participated to fulfill a class requirement. The subjects had normal or corrected-to-normal vision, and were naive to the purpose of the experiment.

Apparatus, stimuli, and procedure. The apparatus and stimuli were identical to those for Experiment 1, with the exception that the fixation cross always appeared in the center of the screen. In other words, the display consisted of one-half of that used for Experiment 1, located in the middle of the screen.

For each trial, the timing of the sequence of events was as follows. First, the fixation cross was presented in the center of the display and remained present for 500 ms. Immediately following the disappearance of the fixation cross, two boxes were shown both either to the left or right of the fixated location. One of these boxes contained the imperative stimulus. The boxes and stimulus remained present until the response was made. As in Experiment 1, a tone sounded if the response was incorrect, and the intertrial interval was 1 s.

Each subject was tested with all three sets of stimuli in distinct blocks of 16 practice trials and 160 test trials, with the order of conditions counterbalanced across subjects. The test trials within each block were comprised of 20 trials for each stimulus in each of the 4 locations. The order of the trial types was randomized within each session.

Results

The percent of incorrect responses was 3.40. RTs for incorrect responses were excluded from the analysis. For each subject, the mean RTs and EPs were calculated for each of the combinations of hemispace, relative position, stimulus type, and response. The results are summarized in Table 2.

Reaction times. The main effect of stimulus type, $F(2, 70) = 228.22$, $p = .0001$, $MSE = 7{,}358$, indicated that the responses to the red/green stimuli ($M = 439$ ms) were faster than those to the circle/square stimuli ($M = 484$ ms), which were faster than those to the rectangle/square stimuli ($M = 588$ ms); the main effect of hemispace, $F(1, 35) = 8.28$, $p = .0068$, $MSE = 826$, reflected faster responses to stimuli in the right hemispace ($M = 500$ ms) than in the left hemispace ($M = 506$ ms). Hemispace interacted with relative position, $F(1, 35) = 202.07$, $p = .0001$, $MSE = 645$, with the stimuli closer to the fixation responded to faster than those further away (Ms = 491 and 515 ms, respectively). The three-way interaction of these variables with stimulus type was also significant, $F(2, 70) = 58.91$, $p = .0001$, $MSE = 665$. The advantage for stimuli closer to fixation was largest for the rectangle/square set, intermediate for the circle/square set, and smallest for the red/green set.

The interaction effect of hemispace (stimulus side) and response was significant, $F(1, 35) = 18.31$, $p = .0001$, $MSE = 1{,}339$. Although the three-way interaction of these variables with stimulus type was not significant, $F(2, 70) = 1.96$, $p = .1485$, $MSE = 848$, the individual analyses showed a significant hemispace × response interaction for the red/green set, $F(1, 35) = 11.31$, $p = .0019$, $MSE = 1{,}102$, and for the circle/square set, $F(1, 35) = 25.23$, $p = .0001$, $MSE = 535$, but not for the rectangle/square set, $F(1, 35) = 1.35$, $p = .2539$, $MSE = 1{,}399$. The Simon effect for hemispace was 13 and 14 ms for the red/green and circle/square sets and 5 ms for the rectangle/square set. The interaction between relative position and response was not significant, $F(1, 35) = 0.63$, $p = .4324$, $MSE = 628$, nor was the three-way interaction of these variables with stimulus type, $F(2, 70) = 1.03$, $p = .3608$, $MSE = 918$.

Table 2 Experiment 2: Mean reaction times in milliseconds and error percentages (in parentheses) as a function of stimulus type, hemispace (stimulus side), relative position, and response

	Hemispace (stimulus side)	
	Left	Right
Red/green		
Left relative position		
Left response	443 (4.0)	442 (4.2)
Right response	451 (4.2)	423 (2.9)
Right relative position		
Left response	435 (2.9)	446 (3.8)
Right response	443 (4.0)	429 (3.2)
Circle/square		
Left relative position		
Left response	488 (3.0)	480 (3.0)
Right response	495 (4.0)	460 (1.9)
Right relative position		
Left response	474 (2.3)	500 (3.3)
Right response	484 (2.4)	481 (1.8)
Rectangle/square		
Left relative position		
Left response	613 (5.6)	564 (3.8)
Right response	615 (3.7)	554 (2.8)
Right relative position		
Left response	571 (2.8)	622 (5.3)
Right response	560 (2.4)	602 (4.4)

Error percentage. The only significant effect was the interaction between relative position and hemispace, $F(1, 35) = 12.92$, $p = .001$, $MSE = .0014$. Stimuli closer to the fixation were responded to more accurately than those further away.

Reaction time distributions. An RT distribution bin analysis was performed as in Experiment 1 for the leftmost and rightmost stimulus locations. For those stimulus locations, the two spatial codes are in agreement and either correspond or do not correspond with the response location. These difference scores, averaged across subjects, are shown in Fig. 7. All three stimulus

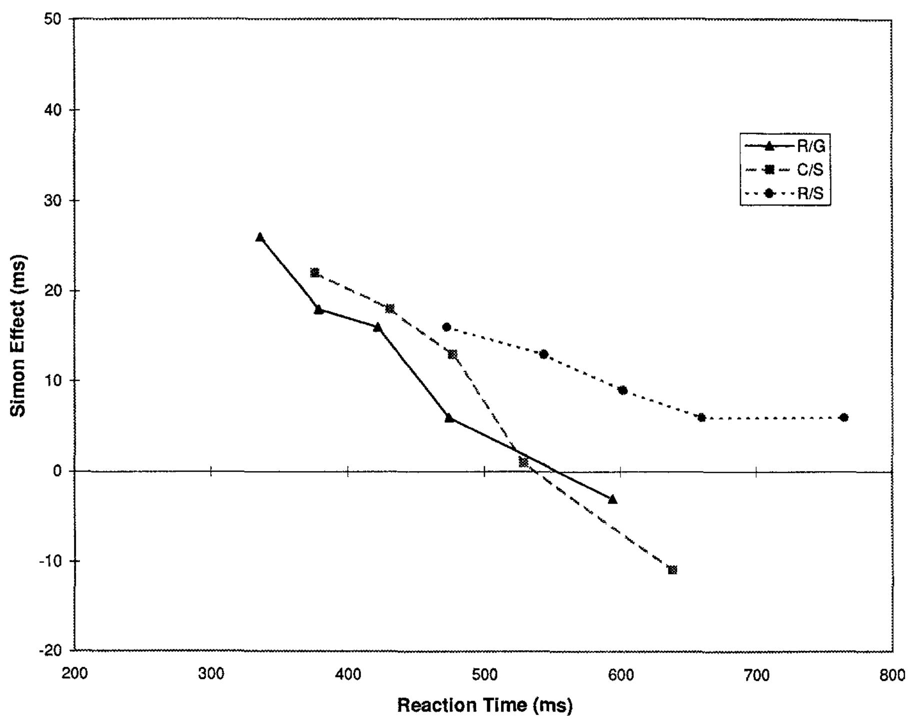

Fig. 7 The Simon effect for the red/green (R/G), circle/square (C/S), and rectangle/square (R/S) stimulus sets in Experiment 2 as a function of 20% RT bins

types showed decreasing Simon effects as RT increased, as would be expected if the spatial codes were decaying.

Discussion

The results are consistent with Experiment 1, providing confirming evidence regarding the effects of different stimulus sets and the role of temporal overlap. First, as in Experiment 1, the color stimuli were more easily identified than the form stimuli, and within the form stimuli the more distinct circle/square set was more easily identified than the rectangle/square set. Second, a significant Simon effect for hemispace (stimulus side) occurred for the red/green and circle/square sets, but not for the rectangle/square set. This result is consistent with the findings of Lamberts et al.'s (1992) Experiment 2 and of Hommel (1994). The absence of the Simon effect for the most difficult stimulus set is in agreement with the temporal overlap hypothesis.

Third, a Simon effect for relative position did not occur for any of the sets of stimuli. This finding is consistent with the results of Hommel's (1994), Umiltà and Liotti's (1987), and Stoffer's (1991) experiments. Hommel noted that this finding conflicts with the finding of a Simon effect with respect to relative position in the Lamberts et al. (1992) task variation. He suggested that the procedural difference that caused the conflicting findings may have been the relatively large stimuli and boxes used by Lamberts et al. However, our Experiment 2 used the same stimulus and box sizes as our Experiment 1, yet only Experiment 1 showed a Simon effect with respect to relative position. Thus, the size of the display elements does not seem to be a crucial factor. Because the overall RTs in Experiment 2, which did not show a relative position effect, were similar to those of Experiment 1, which did, the absence of this effect suggests that codes for relative position were not formed in Experiment 2.

Thus, in contrast to Experiment 1, the results of Experiment 2 are inconsistent with the hypothesis that location is coded automatically with respect to all frames of reference. The major procedural difference between Experiment 1, in which evidence for relative location coding was obtained, and this experiment, in which it was not, is that the fixation cross appeared in the left or right periphery in the former experiment but in the center of the screen in the latter. Thus, whereas eye movements were likely – and possibly even necessary – in Experiment 1, fixation could be maintained throughout the trial in Experiment 2. The shifting of attention, and likely of fixation, to the location cued by the fixation cross in Experiment 1 could have led to continued shifting of attention to the target location. In Experiment 2, the likelihood of maintaining fixation could have led to a more global identification strategy in which the last step is zooming, as Stoffer (1991) suggested. Thus, attention shifting may be playing a role in location coding, even though the location codes decay across time in the manner implied by Hommel's (1994) temporal overlap hypothesis.

Experiment 3

This experiment was conducted to look at multiple reference markers in a previously untested variation of the Simon task. The four locations in which the stimulus could occur are presented in Fig. 8. The positions resulted from a theoretical layout of the cockpit environments of some fighter aircraft. The control panel of some fighter aircraft is designed in a wrap around layout. The pilots have a large panel directly in front of them and two smaller panels, one to their left and to their right side. This creates a left and right division based on the midline of the bodies with the front panel, and two additional left and right divisions are created where the front and left panel intersect and where the front and right panel intersect (Robinson, 1979). This layout allows for coding based on multiple frames of reference; it does not seem to be conducive to attentional zooming of the type proposed by Stoffer (1991) because the target stimulus is not embedded within a larger object. Thus, if no Simon effect based on relative position is found, the absence of the effect cannot be attributed to attentional zooming. The temporal overlap hypothesis would lead to the expectancy that if the Simon effect is found for both frames of reference, it should decrease in magnitude as RT increases.

The experimental procedure was as follows. First, three vertical lines appeared on the visual display. One line was in the horizontal center of the display, with a second line to the left of the center line and a third line to the right of the center line. The lines remained present throughout the trial and served to demarcate the possible stimulus locations. In the second stage of each trial, one of the imperative stimuli appeared in one of the four locations. The geometrical shape or color of the stimulus determined which response, a left or right keypress, was to be made.

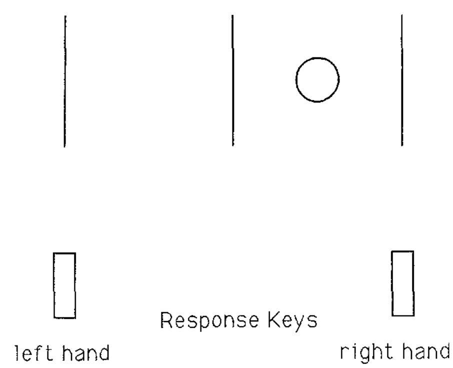

Fig. 8 Schematic diagram of the display condition used in Experiment 3

Method

Subjects. Ninety-six students from the same pool as in Experiment 1 participated to fulfill a class requirement. The subjects had normal or corrected-to-normal vision, and were naive to the purpose of the experiment.

Apparatus and stimuli. The apparatus was identical to Experiment 1. The stimuli used were identical, except for size. The circles were 6 mm (.63°) in diameter, the square was 5 mm (.52°), and the rectangle was 7 mm (.73°) in length and 4 mm (.42°) in width. The lines were 1 mm (.10°) in width and 12 mm (1.25°) in height, and were 36 mm (3.75°) apart from one another. The stimulus was always presented in the center between one of the outside lines and the center line, or an equal distance to the left of the leftmost line, or to the right of the rightmost line.

Procedure. For each trial, the timing of the sequence of events was as follows. First, the lines appeared in the center section of the display and remained on throughout the trial. One second following the onset of the lines, a stimulus appeared in one of the four locations. The lines and stimulus remained present until a response was made. After the response, a tone sounded if the response was incorrect. The intertrial interval was 1 s.

Subjects performed with only one set of stimuli. Thirty-two subjects were randomly assigned to each condition. The instructions regarding how to respond to the stimuli were the same as those in Experiment 1. Each subject took part in one experimental session. The session consisted of 24 practice trials and 192 test trials. The test trials were comprised of 48 trials for each of the four experimental conditions. The order of the trial types was randomized within each session.

Table 3 Experiment 3: Mean reaction times in milliseconds and error percentages (in parentheses) as a function of stimulus type, hemispace (stimulus side), relative position, and response

	Hemispace (stimulus side)	
	Left	Right
Red/green		
Left relative position		
Left response	442 (2.5)	453 (4.4)
Right response	475 (6.4)	426 (2.4)
Right relative position		
Left response	439 (2.8)	472 (5.4)
Right response	450 (3.7)	431 (2.4)
Circle/square		
Left relative position		
Left response	497 (1.7)	509 (3.5)
Right response	521 (5.4)	476 (1.7)
Right relative position		
Left response	480 (2.4)	534 (3.7)
Right response	493 (4.7)	501 (2.0)
Rectangle/square		
Left relative position		
Left response	538 (2.3)	532 (3.4)
Right response	564 (5.8)	511 (1.8)
Right relative position		
Left response	518 (2.4)	556 (6.2)
Right response	505 (4.1)	548 (2.8)

Results

The percent of incorrect responses was 3.49. RTs for incorrect responses were excluded from the analysis. For each subject, the mean RTs and EPs were calculated for each of the combinations of hemispace (left vs. right), relative position (left vs. right), stimulus type, and response. The results are summarized in Table 3.

Reaction times. The main effect of stimulus type was significant, $F(2, 93) = 19.05$, $p = .0001$, $MSE = 25{,}107$, reflecting that the responses to red/green stimuli ($M = 448$ ms) were faster than those to the circle/square stimuli ($M = 501$ ms), which were faster than those to the rectangle/square stimuli ($M = 534$ ms). There was also a main effect of response, $F(1,93) = 7.01$, $p = .0095$, $MSE = 934$, with right keypresses ($M = 492$ ms) being faster than left keypresses ($M = 498$ ms).

There was no main effect of hemispace, but the interaction between hemispace and stimulus type was significant, $F(2,93) = 5.50$, $p = .0055$, $MSE = 603$, showing faster responses to the stimuli in the two left locations than those in the two right locations for the red/green stimulus set, and the reverse pattern for the circle/square and rectangle/square stimulus sets. There was also a significant interaction of relative position and hemispace, $F(1, 93) = 217.76$, $p = .0001$, $MSE = 514$, showing that the outer positions were responded to slower than the inner positions (Ms = 507 and 483 ms, respectively). The three-way interaction of these variables with stimulus type was significant as well, $F(2, 93) = 15.16$, $p = .0001$, $MSE = 514$, with the advantage for the inner positions being 13, 24, and 36 ms for the red/green, circle/square, and rectangle/square conditions, respectively.

The Simon effect for hemispace was obtained, as indicated by a response × hemispace interaction, $F(1, 93) = 117.06$, $p = .0001$, $MSE = 754$. RTs averaged 484 ms when hemispace and response location corresponded and 505 ms when they did not. This effect was significant for all three sets of stimuli: red/green, $F(1, 31) = 76.73$, $p = .0001$, $MSE = 664$; circle/square, $F(1, 31) = 75.07$, $p = .0001$, $MSE = 564$; and rectangle/square, $F(1, 31) = 6.69$, $p = .0146$, $MSE = 1034$, although hemispace and response location entered into a three-way interaction with stimulus type, $F(2, 93) = 7.90$, $p = .0007$, $MSE = 754$. The size of the Simon effect decreased from red/green to circle/square to rectangle/square (Ms = 29, 25, and 10 ms, respectively).

A Simon effect for relative position was also evident, with relative position interacting significantly with response, $F(1, 93) = 20.08$, $p = .0001$, $MSE = 376$. This pattern held for all three stimulus types (Ms = 9, 3, and 7 ms for the red/green, circle/square, and rectangle/square sets, respectively), as indicated by the absence of a three-way interaction involving stimulus type, but the Simon effect for relative position was not significant for the circle/square stimuli.

The three-way interaction of relative position × hemispace × response was significant as well, $F(1,93) = 10.90$, $p = .0014$, $MSE = 632$, showing a significantly larger Simon effect for the outer positions than for the inner positions (Ms = 28 and 15 ms, respectively). The four-way interaction of relative position × hemispace × response × stimulus type was significant, too, $F(2,93) = 3.81$, $p = .0258$, $MSE = 632$, demonstrating that this difference in Simon effect magnitudes for the inner and outer positions tended to be larger for the stimulus sets to which responding was faster.

Error percentage. The ANOVA produced three significant effects, the interactions of relative position × hemispace, $F(1,93) = 11.92$, $p = .0008$, $MSE = .0009$, hemispace × response, $F(1,93) = 77.21$, $p = .0001$, $MSE = .0015$, and relative position × response, $F(1,93) = 7.38$, $p = .0079$, $MSE = .0014$. The first interaction reflects responses being more accurate for stimuli in the two inner locations compared to the two outer locations, and the remaining two interactions indicate Simon effects for response accuracy as a function of hemispace and relative position, respectively.

Reaction time distributions. An RT distribution bin analysis was performed as in the previous experiments for the leftmost and rightmost stimulus locations. These difference scores, averaged across subjects, are shown in Fig. 9. As in Experiment 1, the circle/square and rectangle/square conditions showed Simon effects of decreasing magnitude as RT increased, whereas the red/green condition did not.

Discussion

The experiment yielded results in a previously untested variation of the Simon task that are consistent with those of Experiments 1 and 2. First, the main effect of stimulus demonstrates that the color stimuli were more easily identified than the form stimuli, and within the form stimuli the more distinct circle/square set was more easily identified than the rectangle/square set. This result was the same as those found in Experiments 1 and 2, and is consistent with Hommel's (1994) findings and his temporal overlap hypothesis.

Second, a Simon effect was found for all three stimulus sets. Moreover, the Simon effect decreased in size as identification time for the respective stimulus sets increased, as Hommel's (1994) temporal-overlap hypothesis would predict. The effect size was largest for the red/green set, which is most easily identified, smallest for the rectangle/square set, which is most difficult to identify, and intermediate for the circle/square set, which falls in the middle in terms of identifiability. The distributional analyses showed the size of the Simon effect to decrease as RT increased within the circle/square and rectangle/square sets. However, as in Experiment 1, the red/green stimulus set showed no tendency for the Simon effect to decrease as RT increased.

Third, the outer positions, which have consistent position cues from both the center line and its outer reference line, had a larger Simon effect size than did the inner positions, which have conflicting spatial cues from the center line and its outside reference line. This result provides additional confirmation of Lamberts et al.'s (1992) Experiment 2 and to the present study's

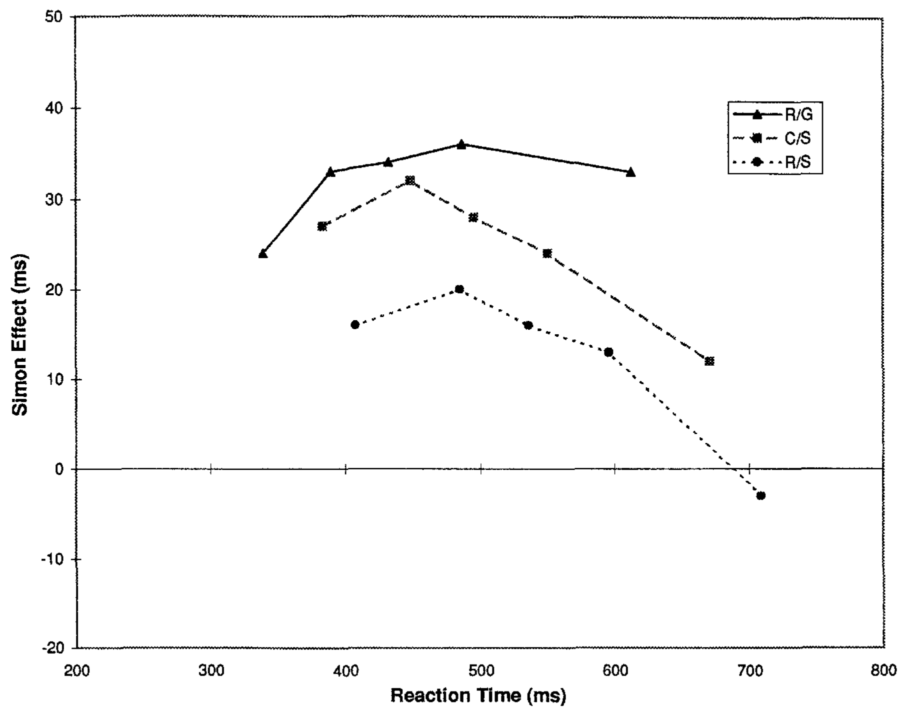

Fig. 9 The Simon effect for the red/green (R/G), circle/square (C/S), and rectangle/square (R/S) stimulus sets in Experiment 3 as a function of 20% RT bins

Experiment 1 for coding with respect to multiple frames of reference.

There are at least two possible explanations for why relative position influenced RTs in Experiment 3 but not in Experiment 2. In Experiment 2, the stimuli were embedded within boxes; according to Stoffer (1991), the last step in shifting attention to the target stimulus in that situation would be to zoom in on the stimulus, and thus relative location would not be coded. In Experiment 3, the stimuli were not embedded within boxes, rendering such attentional zooming unlikely. If shifting of attention from the central line to one of the outer lines and then to the target stimulus were occurring, then a relative position code would be generated. Another major difference in the two experiments is that in Experiment 2 the boxes distinguishing relative position appeared simultaneously with the target stimulus, whereas in Experiment 3 the lines demarcating the four possible locations appeared in advance of the target stimulus. Thus, the stimulus event was the only change within clearly marked frames of reference in Experiment 3, whereas that event occurred along with the onset of the relative location frame in Experiment 2.

It is interesting to compare our results in Experiment 3 to those obtained by Umiltà and Liotti (1987) and Stoffer (1991) when the onset of the boxes preceded the target stimulus. In that situation, they found a Simon effect with respect to relative location but not to hemispace. Hemispace was specified in their experiments when the reference boxes appeared, leaving only an explicit reference frame for relative location, whereas the reference lines in our experiment did not specify the hemispace in which the target stimulus would occur prior to its presentation. Therefore, the reference lines explicitly distinguished not only relative location within a hemispace but also the hemispace itself.

Experiment 4

In studies of S-R compatibility proper, the relevant stimulus attribute is its location. Hence, when multiple reference frames are present, the task requires that the stimulus location be coded with respect to the frame that is defined as relevant. Umiltà and Liotti (1987) and Stoffer (1991) examined S-R compatibility proper for the version of the four-location task in which a pair of boxes, presented to the left or right of fixation, designated the possible locations. Only the relevant relative-location reference frame influenced the compatibility effect size, and, in contrast to the results that they obtained for the Simon effect, this effect was equally large when the boxes and imperative stimulus occurred simultaneously as when they were presented successively. Umiltà and Liotti also conducted an S-R compatibility experiment to evaluate whether coding could occur with respect to hemispace when that reference frame was defined as relevant. In their Experiment 2, four boxes, two on each side of fixation, appeared. One of the boxes in each pair was shown in solid contours and one in broken contours. The broken contour boxes (both in the left relative locations of their respective hemispaces or in the right relative locations) had only the purpose of marking the relative position of the stimulus, which appeared in one of the two solid contour boxes. The results were similar to those described above, in that only the relevant frame (in this case, hemispace) resulted in a compatibility effect.

Although the results of this latter experiment suggested location-coding with respect to hemispace, Umiltà and Liotti (1987) noted that an alternative possibility was that the two broken contour boxes were effectively ignored and that relative locations of the two solid contour boxes became the relevant frame. The display used in Experiment 3, when used for an S-R compatibility task, can provide a stronger test of whether relative location is coded when hemispace is defined as the relevant frame. Experiment 4 thus used a display format similar to that used in Experiment 3, but the stimulus was an asterisk and subjects were instructed to respond to the stimulus based on its location with respect to hemispace. Half of the subjects responded with a spatially compatible S-R mapping and half with an incompatible mapping.

Method

Subjects. Twenty-eight students from the same pool as in Experiment 1 participated to fulfill a class requirement. The subjects had normal or corrected-to-normal vision, and were naive to the purpose of the experiment.

Apparatus, stimuli, and procedure. The apparatus used was identical to that in Experiment 3, except that the stimulus was an asterisk 3 mm (.31°) in height and 3 mm (.31°) in width, and the reference lines were 1 mm (.10°) in width and 8 mm (.83°) in height, and were 30 mm (3.12°) apart from one another.

On each trial, the timing of the sequence of events was the same as in Experiment 3. The instructions were given in terms of the location of the stimulus. Half of the subjects were instructed to make a left response if the asterisk appeared in one of the two positions to the left of center and to make a right response if the asterisk appeared in one of the two positions to the right of center, and half of the subjects received the reverse S-R mapping. Each subject took part in one experimental session. The session consisted of 12 practice trials and 120 test trials. The test trials were comprised of 30 trials for each of the four locations. The order of the trial types was randomized within each session.

Results

The percent of incorrect responses was 2.70. RTs for incorrect responses were excluded from the analysis. For each subject, the mean RTs and EPs were calculated for each of the combinations of hemispace (left vs. right), relative position (left vs. right), and response (left vs. right). The results are summarized in Table 4.

Reaction times. The main effect of response, $F(1, 27) = 11.54$, $p = .0021$, $MSE = 618$, was significant, with right responses being faster than left responses (Ms = 399 and 411 ms, respectively). There were significant interactions of relative position and hemispace, $F(1,27) = 9.24$, $p = .0052$, $MSE = 554$, and hemispace and response, $F(1,27) = 97.82$, $p = .0001$, $MSE =$ 6,682. Responses were slower to inner stimuli than to outer stimuli (Ms = 410 and 400 ms, respectively) and faster for compatible responses than for incompatible responses (Ms = 351 and 459 ms, respectively). Relative position also interacted with response, $F(1,27) = 4.91$, $p = .0354$, $MSE = 475$, but the responses were faster when the position did not correspond with that of the response than when it did (Ms = 402 and 408 ms, respectively).

Error percentage. The ANOVA indicated only two significant effects. The interaction of relative position × hemispace, $F(1, 27) = 15.17$, $p = .0006$, $MSE = .0009$, reflects less accurate responses to inner stimuli than to outer stimuli (EPs = 3.49 and 1.92%, respectively). The hemispace × response interaction, $F(1, 27) = 75.27$, $p = .0001$, $MSE = .0006$, showed more errors for the incompatible mapping ($EP = 4.2\%$) than for the compatible mapping ($EP = 1.2\%$).

Reaction time distributions. An RT distribution bin analysis was performed as in the previous experiments for the leftmost and rightmost stimulus locations. These difference scores, averaged across subjects, are shown in Figure 10. Unlike Experiments 1–3, in which stimulus location was irrelevant, the magnitude of the compatibility effect increased markedly as RT increased. The fact that the function is monotonically increasing, with no sign of a plateau, suggests that it likely is not due just to a floor effect for RTs with the compatible mapping.

Table 4 Experiment 4: Mean reaction times in milliseconds and error percentages (in parentheses) as a function of hemispace (stimulus side), relative position, and response

	Hemispace (stimulus side)	
	Left	Right
Left relative position		
Left response	355 (0.5)	472 (4.8)
Right response	447 (3.9)	344 (2.0)
Right relative position		
Left response	361 (1.8)	455 (2.6)
Right response	462 (5.4)	344 (0.7)

Discussion

As expected, an effect of spatial compatibility proper with respect to the defined relevant frame of hemispace was found. Responses to stimuli positioned to the left of center were faster when the assigned response was left than when it was right, and the reverse relation held for stimuli positioned to the right of center. There was also an effect of relative position, with responses 6 ms faster on average when relative location did not correspond to the response location than when it did. Note that

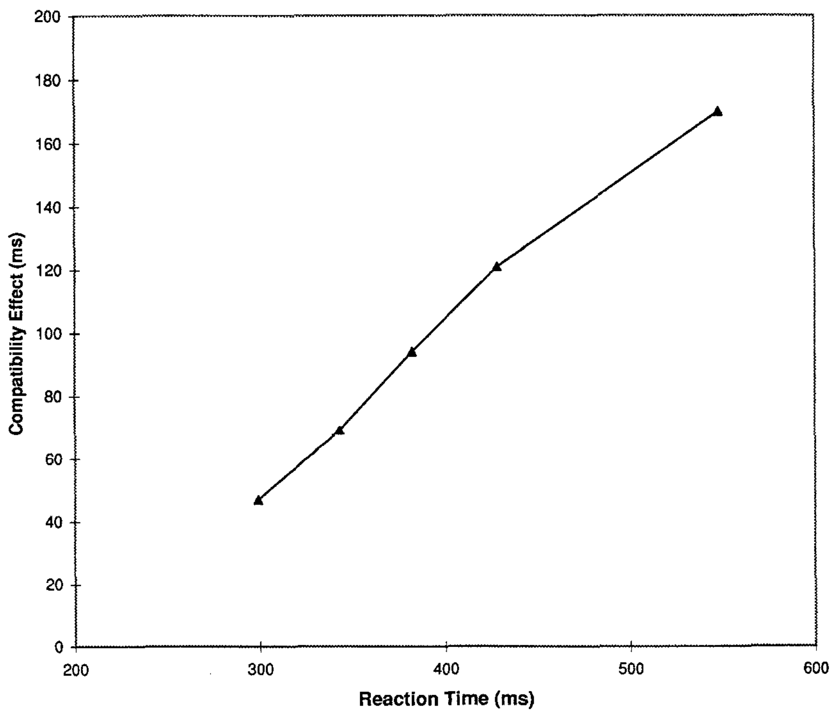

Fig. 10 The S-R compatibility effect as a function of 20% RT bins in Experiment 4

this small effect is in the opposite direction of that expected if a relative location code were being formed. This finding adds converging evidence to support the conclusion of Umiltà and Liotti (1987) that when hemispace is designated as the relevant frame, a relative position code is not automatically formed. Further, this is in agreement with many other findings, such as those of Umiltà and Liotti (1987), Stoffer (1991), and Nicoletti, Anzola, Luppino, Rizzolatti, and Umiltà (1982), whose results indicate that a hemispace code is not automatically formed under at least some circumstances when relative location is defined as the relevant frame.

Hommel (in press) has proposed that the location codes decay only when they are irrelevant to the task. The hemispace code was defined as relevant for the task performed in Experiment 4. Hence, it is not surprising that decay functions of the type evident for the Simon effect in Experiments 1–3 were not apparent in Experiment 4.

General discussion

The present experiments combined aspects of the experiments conducted by Umiltà and Liotti (1987), Stoffer (1991), Lamberts et al. (1992), and Hommel (1994) to resolve discrepancies regarding the nature of spatial coding. Experiments 1–3 examined variations of the Simon effect (i.e., the effect of irrelevant location information on performance) using the three stimulus sets (red/green, circle/square, and rectangle/square) used in one or more of the previous studies. Experiment 4 examined S-R compatibility proper to evaluate whether spatial coding occurs in a similar manner when stimulus location is relevant.

Experiment 1 showed in a replication of Lamberts et al.'s (1992) eight-location task that the color stimuli were identified faster than the form stimuli, with the more distinct circle/square set being identified faster than the rectangle/square set. Overall, Simon effects were obtained for all three frames of reference, consistent with Lamberts et al.'s findings and with the hypothesis that multiple spatial codes are formed. The Simon effect for hemifield was largest in magnitude; it was significant for all three sets of stimuli, with the size of the effect decreasing as the time to identify the stimuli in the specific set increased. The Simon effect for relative position was significant for the red/green set and the circle/square set, but not for the rectangle/square set. The Simon effect for hemispace was small, being significant only for the red/green set, but not for the circle/square set or for the rectangle/square set. The analyses of the RT distributions for the two outermost stimulus locations, for which the location codes with respect to all three frames of reference were the same, showed decreasing Simon effect sizes as RT increased for the two form sets but not for the red/green set. Thus, most but not all of the results conformed well with the predictions of the temporal overlap hypothesis.

Experiment 2 was a replication of Umiltà and Liotti's (1987) four-location task. Consistent with Experiment 1, the color stimuli were more easily identified than the form stimuli, with the more distinct circle/square set being more easily identified than the rectangle/square set. A Simon effect for hemispace (stimulus side) occurred for the red/green set and the circle/square set, but not for the rectangle/square set, with the size of this Simon effect decreasing in the direction of the stimulus sets from easiest to most difficult to identify. Unlike Experiment 1, no Simon effect with respect to relative position was evident for any of the stimulus sets. The distributional analysis of RTs for the outer positions showed the Simon effect to be a decreasing function of increasing RT for all three stimulus sets.

Experiment 3 used a previously untested version of the Simon task in which the four stimulus locations were demarcated by three vertical lines. As in the previous experiments, the color stimuli were more easily identified than the form stimuli, with the more distinct circle/square set being more easily identified than the rectangle/square set. Simon effects with respect to hemispace and relative location were found for all three stimulus sets. The Simon effect decreased in size from the red/green to the circle/square to the rectangle/square set, and the distributional analysis showed the Simon effect for all but the red/green set to decrease as RT increased.

Experiment 4, which used a layout similar to that of Experiment 3, was a spatial compatibility task in which subjects indicated whether the location of an asterisk was left or right of center. The results of this experiment were consistent with prior studies of spatial compatibility proper in showing a significant compatibility effect with respect to the relevant frame of reference, hemispace. The distributional analysis showed that the compatibility effect did not decrease as RT increased, unlike the most commonly obtained pattern for the Simon effect.

Multiple codes hypothesis

The present study was conducted in part to determine whether the results of Lamberts et al.'s (1992) Experiment 2 that imply coding with regard to multiple frames of reference could be replicated and found in other experimental conditions. The results of Experiment 1, showing Simon effects for the frames of hemifield, relative position, and hemispace in a direct replication of Lamberts et al.'s Experiment 2, provide additional confirmation for the multiple codes hypothesis. The pattern of results clearly demonstrated that as the spatial codes from different reference frames became more conflicting, the Simon effects decreased or disappeared. This is important, as the Lamberts et al. study was the only experiment in which these types of results had been reported. Experiment 3 showed similar evidence for spatial coding with respect to multiple frames of reference for a display in which the stimulus locations were demarcated by three vertical lines that remained in view throughout each trial. In this experiment, Simon effects were found for both hemispace and relative position. Furthermore, the outer positions, which have consistent position cues, had a larger Simon effect size than did the inner positions which have conflicting spatial cues.

Experiment 2, which used a similar layout to Experiment 1 except for having only four stimulus locations, as in Umiltà and Liotti's (1987) Experiment 3, showed evidence for spatial coding with respect to hemispace but not to relative position within the hemispace. This lack of evidence for relative position coding with the type of display used by Umiltà and Liotti is in agreement with their data as well as with those of Stoffer (1991) and Hommel (1994). One possibility is that coding with respect to relative position occurs with this display, as it does for the displays used in Experiments 1 and 3, but was not evident because the relative position code decayed prior to response selection. Although this possibility cannot be ruled out entirely, the data do not seem to be consistent with such an interpretation. The display used in Experiment 2, which did not yield a relative position effect, was virtually identical from the presentation of the fixation cross onward to that used in Experiment 1, which did yield a relative position effect. Moreover, the RTs in the two experiments were similar. A second, and more likely, possibility is that relative position was not coded in Experiment 2. Perhaps when the fixation is constant, a strategy can be adopted that treats the two boxes as a whole, thereby ignoring their left-right distinction, much as Stoffer's attention-zooming concept implies. Coding with respect to relative position also does not seem to have occurred in the spatial compatibility task used in Experiment 4, for which location with respect to hemispace was defined as the relevant stimulus dimension. Thus, although the data support the hypothesis that multiple spatial codes can be formed, they suggest that this is not done automatically and that there is a role for encoding strategies, as implied by Stoffer's attention-shifting account.

Temporal overlap hypothesis

A second issue was whether the temporal overlap hypothesis postulated by Hommel (1994) is sufficient to account for the discrepancies between the results of Umiltà and Liotti (1987) and Stoffer (1991) and those of Lamberts et al. (1992). On the whole, the results of the first three experiments conformed closely to predictions of the temporal-overlap hypothesis. These three experiments consistently showed a decrease in the size of the Simon effect as the stimulus sets became increasingly difficult to identify and the RT increased. Further, the results of Experiments 1 and 2 showed that even when the reference boxes and imperative stimulus appeared simultaneously, a condition in which attentional zooming should occur, according to Stoffer (1991), a Simon effect was found for stimuli that permitted rapid identification. Finally, the data from Experiment 3 showed the pattern of results predicted by Hommel's temporal overlap hypothesis in a task that should not allow for attentional zooming, with the Simon effect again being larger for the stimuli that permitted rapid identification. Thus, regardless of whether the situation was one that should allow attentional zooming or shifting, the Simon effect was present for the stimuli that could be identified rapidly and was of lesser magnitude or absent for those that took longer to identify.

The analyses of the RT distributions for each stimulus set in the three experiments also showed evidence for the temporal overlap hypothesis. When the Simon effect was calculated for the two outermost stimulus locations, for which the spatial codes for all frames of reference coincide, seven out of the nine conditions in the three experiments showed the effect size to be a decreasing function of RT, as predicted by the view that the irrelevant location code decays. The two exceptions were in Experiments 1 and 3 for the red/green stimulus set. In both of these cases, the Simon effect remained essentially constant throughout the RT distribution. On the surface, these exceptions are inconsistent with the temporal overlap hypothesis. However, Hommel (in press) has shown that functions such as these can be obtained if some aspect of the task requires that the location code be maintained, even though the code is irrelevant in terms of the S-R mapping. Although there is no obvious reason why location would be maintained for the red/green stimuli in Experiments 1 and 3 but not for the form stimuli in any of the experiments or for the red/green stimuli in Experiment 2, we cannot rule out this possibility.

Summary

The experiments showed confirming evidence for Lamberts et al.'s (1992) finding that location coding can occur with respect to multiple frames of reference. In Experiments 1 and 3, the Simon effects were greatest for those positions which had the same spatial codes, and smaller or absent for those positions in which the spatial codes became more conflicting. However, the fact that no evidence for coding of relative stimulus position was obtained for the Simon task in Experiment 2 or the spatial compatibility task of Experiment 4 suggests that code formation is not an automatic consequence of the display. The results of Experiment 2 suggest that Stoffer (1991) may be correct in assuming that a location code is not formed under conditions of attention zooming. Further, the experiments showed confirming evidence for Hommel's (1994) temporal overlap hypothesis. In all three experiments that investigated the Simon effect, the stimulus sets showed increasing RTs from red/green to circle/square to rectangle/square and decreasing Simon effects in the same order. The RT distributions for the respective stimulus sets showed the same overall pattern of decreasing Simon effects with increasing RTs. Thus, the ease of the identification of stimuli (temporal overlap), and the number of consistent spatial cues (multiple frames of reference) are both having an influence on the occurrence, the absence, and the size of the Simon effects.

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