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Stimulus–response compatibility effects in go–no-go tasks: A dimensional overlap account

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According to the automatic response activation hypothesis of the dimensional overlap (DO) model (Kornblum, Stevens, Whipple, & Requin, 1999), stimulus–response compatibility effects are expected to occur in go–no-go tasks. This prediction is confirmed in two experiments in which subjects moved a hand to one side of the field on presentation of a go stimulus. Although the direction of movement was known in advance and the spatial attribute of the go stimuli was irrelevant to the go–no-go decision, the subjects' response time was shorter when the spatial attribute of the go stimulus corresponded to that of the response than when it did not. These effects are shown to depend on the similarity of the go and the no-go stimuli, as well as on whether the spatial attribute of the go stimuli was its actual location or its meaning. We discuss these results in terms of the temporal dynamics of automatic and controlled response processes, as hypothesized in the DO model.

Stimulus–response compatibility (SRC) refers to the fact that some pairings of stimuli and responses lead to faster and more accurate performance than do others. For example, when a set of letters and letter names are used as stimuli and responses, responses are faster and more accurate if each letter is paired with its own name as the response (congruent mapping) than if each letter is paired with the name of another letter in the set (incongruent mapping). SRC effects are usually measured in terms of the difference in reaction time (RT) between congruent and incongruent mapping conditions. Congruent and incongruent RTs are also sometimes compared with a neutral condition in which the stimulus and response sets are unrelated (e.g., digits as stimuli and city names as responses; but see Kornblum & Lee, 1995).

The original studies of SRC by Fitts and co-workers (Fitts & Seeger, 1953) focused on simple perceptual–motor tasks. For example, they found that if a set of stimulus lights was arranged in a square, it was best for the response keys to be arranged in a square as well, with each key corresponding to a light in that position. Here, the relationship between the stimulus and the response sets is physical. However, SRC effects are not limited to physical correspondences. They have also been found in complex tasks in which the stimulus–response (SR) relationship is semantic (e.g., the Stroop task). Furthermore, SRC effects are not restricted to relevant stimuli (i.e., stimulus features with a correlation of one with the response); they can also be produced by stimulus dimensions that are irrelevant (i.e., have a correlation of zero with the response). One of the best known examples of SRC effects with irrelevant stimuli is the Simon effect. In a prototypical Simon task, the responses might consist of left and right keypresses, with stimuli consisting of red or green lights presented to the left or the right of a central fixation point. Even though identification of the correct response would depend on color (i.e., color is relevant), responses are ordinarily faster if the position of the color light corresponds to the position of the response key than if it does not correspond. SRC effects caused by a relevant stimulus are usually much larger in size than those caused by an irrelevant stimulus (see, e.g., Kornblum & Lee, 1995).

The Dimensional Overlap Model: The Automatic Response Activation Hypothesis

The dimensional overlap (DO) model has been proposed as an integrated account for these and many other SRC effects (see Kornblum, 1994; Kornblum, Hasbroucq, & Osman, 1990). For present purposes, we call attention to the model's automatic response activation hypothesis, one of its central tenets. According to this hypothesis, when a stimulus set and a response set are perceptually, conceptually, or structurally similar (i.e., have DO), presentation

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of a stimulus automatically activates its most strongly associated response in the set (i.e., a congruent response), regardless of whether that stimulus is relevant or irrelevant and regardless of the SR mapping assignment in the task. For example, if the response set consists of the utterances "b" and "d," presentation of a colored stimulus letter B would automatically activate the response tendency of saying "b," whether the correct response was determined by the identity or the color of the letter. Furthermore, even if the stimulus B were assigned to the utterance "d" (incongruent mapping), presentation of the letter B would still automatically activate the response tendency of saying "b." An important consequence of this hypothesis, with some additional assumptions from the model, is that many different types of SRC effects can now be shown to be the result of the interplay between this automatically activated response and a controlled response tendency, with the latter reflecting the SR mapping instructions. That is, a particular trial is SR consistent if the stimulus activates an automatic response that corresponds to the correct response, as stipulated for that stimulus in the task. If the automatic response is inconsistent with the correct response, that trial is SR inconsistent.

The automatic response activation hypothesis is well supported by both behavioral and psychophysiological evidence. For example, Osman, Bashore, Coles, and Donchin (1992) had subjects perform a choice RT task in which stimulus location was incongruently mapped to response-key position (left or right) and found that the lateralized readiness potential (LRP) corresponding to the congruent, but incorrect, response emerged briefly before the LRP for the correct response became dominant. Evidently, the congruent response was activated quickly and was eventually overwhelmed by the incongruent response (also see Smulders, 1993). Behavioral evidence of automatic response activation has also recently been reported by Shiu and Kornblum (1996), who, in a task in which subjects were asked to make incongruent naming responses to simple stimuli (e.g., say "plane" to CAR, "car" to BIKE, and so on), found that RT was longer if the correct response for the current trial was the name of the stimulus presented on the preceding trial (e.g., saying "car" to BIKE is slow if preceded by saying "plane" to CAR) than in a control condition in which this intertrial relation did not hold. These negative priming effects (cf. Tipper & Cranston, 1985) strongly suggest that, with incongruent mapping instructions, the tendency to produce the congruent name of the stimulus is automatically activated and subsequently inhibited, after which time its accessibility is momentarily reduced.

Stimulus–Response Compatibility and Go–No-Go Tasks: The Effect of Relevant Stimuli

If the DO model is right about an automatic response (activated by a stimulus) that conflicts with the correct response being the cause of SRC, SRC effects should occur even when the correct response has been selected and fully prepared prior to the presentation of the stimulus. Indeed, SRC effects have been found in go–no-go tasks (Donders' *c* reaction) that used a single, predetermined response. For example, Broadbent and Gregory (1962) had subjects listen to the randomly presented stimulus words *bid* and *did*. In the congruent condition, they responded by saying "bid" to *bid* and made no response to *did*. The word to be uttered as the response was, therefore, known in advance and could be fully prepared. In a separate neutral condition,[1] they responded by saying "deck" to *bid* and nothing to *did*. Broadbent and Gregory found that RT in the congruent condition was 62 msec faster than that in the neutral condition. They also found similar SRC effects in a tactile stimulation experiment in which subjects responded with their right index fingers only to stimulations of their left index fingers (incongruent) and ignored stimulations of their right index fingers or responded only to stimulations of their right index fingers (congruent) and ignored stimulations of their left index fingers. These and other similar results (Callan, Klisz, & Parsons, 1974; Hommel, 1995, Experiment 1; Moscovitch & Smith, 1979) show that SRC effects can, and do, occur in go–no-go tasks.

Kornblum and Zhang (1995) carried the investigation of go–no-go tasks further. In their task, a trial began with a precue (green or red color patch) that specified the verbal response ("H" or "M") to be made to the go stimulus on that trial (see Table 1). The precue stayed on for 1,000 msec and was replaced by either a go or a no-go stimulus. The go stimuli were the letters H and M. Hence, the name of the go stimulus could be either congruent or incongruent with the required response. As is shown in Table 1, SRC effects were obtained when the no-go stimuli were letters (N or W) similar to the go stimuli, but not when the no-go stimuli were blank screens. (The term *SRC effects* here

Table 1
Mean Reaction Times (in Milliseconds) on Go Trials as a Function of Go Stimuli, No-Go Stimuli, and Stimulus–Response (SR) Congruency in Kornblum and Zhang (1995)

Precue	Vocal Response	Stimulus: Go	Stimulus: No-Go	SR Congruency: Congruent (C)	SR Congruency: Incongruent (I)	I−C
Red, green	"H," "M"	H, M	blank	310	311	1
Red, green	"H," "M"	H, M	N, W	394	422	28*

*$p < .05$.

refers to the fact that RT was faster when the identity of the go stimulus was congruent with the required response than when it was incongruent.)

Note that when the go stimuli were letters and the no-go stimuli were blank screens, mere detection of the go stimulus was sufficient for making the go–no-go decision; this led to short average RTs. However, when the go and the no-go stimuli were both letters, the go stimulus had to be identified in order to make the go–no-go decision; this led to long average RTs. Because SRC effects were found in the latter condition only, these effects appear to be contingent on the go stimuli's being identified.

Stimulus–Response Compatibility in Go–No-Go Tasks: The Time Course of Processing and the Effect of Irrelevant Stimuli

Kornblum and Zhang's (1995) failure to obtain SRC effects when the no-go stimuli were blank screens and their success in obtaining them when the no-go stimuli were letters can, in principle, be accounted for by the DO model. Recall that the model assumes that SRC effects are the results of the interplay between automatic and controlled response processes. If one process occurs in the absence of the other or if one is greatly delayed with respect to the other, SRC effects are not expected to occur. Temporal overlap between the processes or their consequences is, therefore, an important condition for obtaining SRC effects (see Kornblum, Stevens, Whipple, & Requin, 1999). Let us now reexamine the Kornblum and Zhang results in this light.

As we have already indicated, when the no-go stimuli are blank screens, mere detection of a stimulus is sufficient for a go decision. Because detection is fast, as compared with identification, it is very possible, in fact quite likely, that when a go response is triggered by the detection of a go stimulus, automatic response activation (which is contingent on the go stimulus' being identified) is still very close to baseline level and much delayed, even in the best of circumstances. This would preclude the occurrence of a significant temporal overlap between the controlled and the automatic processes in this task. Accordingly, it would lead to no SRC effects being observed. This analysis is consistent with De Jong, Liang, and Lauber (1994) and Hommel (1993a, 1994). It also suggests that if, in a go–no-go task, one could produce an automatic response that began early enough, one might be able to produce SRC effects even when the go–no-go decision was made on the basis of a detection (i.e., with blank screens as no-go stimuli). We suggest that an automatic response that was contingent on stimulus localization might be such a candidate.

Coding of stimulus location is accomplished very early in vision. The location coding that starts in the retina persists through the lateral geniculate nucleus to V1 and other cortical visual areas. In agreement with the physiology of the visual system, there is ample psychophysical evidence that detection of simple stimuli is mediated by perceptual mechanisms that are spatially organized (Graham, 1989). Psychophysical evidence also indicates that stimulus detection is closely bound up with stimulus localization. In Sagi and Julesz (1985), for example, the observers were able simultaneously to detect and to locate vertical or horizontal line segments among diagonal line segments, using a fast parallel process (whereas identification of the specific orientation of the targets requires a slow serial process). Sagi and Julesz also found that detection and localization accuracy reaches asymptote at the same stimulus exposure time (see, also, Johnston & Pashler, 1990).

On the basis of this evidence, it seems reasonable to assume that stimulus localization is very fast—perhaps, even as fast as stimulus detection. Therefore, according to the DO model, given a task with lateralized (left/right) responses, an automatically activated response triggered by stimulus localization would affect the latency of a fast (lateralized) go response that was triggered by stimulus detection. The experimental paradigm that incorporates all the necessary components of such a test is the go–no-go variant of the Simon task (which we will describe in more detail below). Thus, the DO model would predict that the location of a go stimulus in such a variant would produce SRC effects (i.e., the Simon effect) even if the go stimulus was merely detected and its location was irrelevant to the go–no-go decision. This prediction is, of course, predicated on the assumption that spatial localization is a fast process, even as compared with the speed of detection. If the automatic response process begins too late, as compared with the go–no-go decision, there would be no SRC effect.

Just because a response is automatic, however, does not necessarily mean that it has an early onset. Automatic response processes may begin early or late, depending on the kind of stimulus information that triggers them (see Kornblum et al., 1999). Recent theoretical discussions of the Simon effects have focused on spatial location as the stimulus trigger (see the review by Lu & Proctor, 1995). For example, Nicoletti and Umiltà (1994) suggest that the Simon effect is produced when attention is shifted to the location of a target stimulus. A different account has been proposed by Hommel (1993b), who argues that the Simon effect is produced when the location of the target stimulus is coded in relation to a reference stimulus or frame. In both of these accounts, spatial information is provided by stimulus location, for which processing is rapid. However, when spatial information is provided symbolically (e.g., by word or by arrow), which requires that the stimulus be identified (see, e.g., Simon, Sly, & Vilapakkam, 1981), the automatic response would necessarily be triggered later in time than if it were triggered by stimulus localization (cf. Michaels & Stins, 1997). Whether the spatial information is provided by stimulus location or stimulus identity, the DO model views these as two different ways of evoking automatic responses that will, however, differ in terms of their temporal dynamic properties. Because of these differences in their temporal properties, these two ways of conveying spatial information may produce SRC effects in some conditions and not in others, depending on whether the automatic process that they give rise to overlaps temporally with the controlled response.

The Present Study

Both experiments in the present study used go–no-go tasks in which the responses consisted of pressing a left or a right button and in which the stimuli were presented either to the left or to the right of a central fixation point; some stimuli were presented centrally but included symbolic information that meant left or right. In either case, however, the spatial information in the stimuli was irrelevant; in this sense, these tasks were similar to the standard Simon task. For every type of stimulus used as a go trial, there were two types of no-go trials: The no-go trials consisted of either blank screens or some stimulus. Thus, given the dimensional overlap between the responses and the (irrelevant) spatial attribute of the go stimuli, all other things being equal, one might expect to observe the standard Simon effect in this task: a shorter RT when the stimulus location and the response location matched and a longer RT when they mismatched.

In Experiment 1, irrelevant spatial information was conveyed either by stimulus location or symbolically, by left- and right-pointing arrows. Location information would presumably trigger the automatic response process early, whereas symbolic information would trigger it later. According to the model, the early onset of the automatic process would affect the go response and, hence, produce an SRC effect, even if the go decision was based on stimulus detection, whereas a later onset would only affect the slower go response based on stimulus identification.

In Experiment 2, rather than systematically sampling the effects of automatically activated responses with fast and slow onsets, we attempted to prolong the stimulus processing stage (i.e., the go–no-go decision) by making the discrimination between the go and the no-go stimuli more difficult than it was in Experiment 1. The rationale was as follows. If the go–no-go decision is delayed (by making the discrimination difficult) with respect to the automatically activated response triggered by location information, no SRC effect should be observed. This is because the controlled process will have been delayed to the point that the automatically activated response has dissipated. Previous studies of SRC with choice tasks (e.g., Hommel, 1993a) have used stimulus degradation to delay the moment of choice. Here, we used level of processing of the imperative stimulus as a way of controlling the speed of the decision.

In previous studies of SRC effects with go–no-go tasks (e.g., Callan et al., 1974), subjects usually placed a finger on a response key located to the left or the right side of the body midline and pressed the key as soon as they saw the go stimulus, regardless of its location. It is not clear, with such a procedure, whether the representation (or motor program) of the response requires a left–right dimension. In order to counter this, the subjects in the present experiments were required to move their hand to the left or the right of a central starting position. This ensured that the left–right dimension was an integral part of the representation of the response.

EXPERIMENT 1

In this experiment, the go and no-go stimuli were chosen so that, in some conditions, mere detection of a go stimulus was sufficient for response, whereas in other conditions, some degree of stimulus identification was required (see Table 2). The second major manipulation in this experiment was in the way spatial information was provided. The spatial information was provided either by the location of a go stimulus, which was not dependent on the stimulus' being identified, or by the symbolic meaning of a stimulus (e.g., left- and right-pointing ar-

Table 2
Mean Reaction Times (RT; in Milliseconds) and Movement Times (MT; in Milliseconds) on Go Trials as a Function of Go Stimuli, No-Go Stimuli, and Stimulus–Response (SR) Consistency in Experiments 1 and 2

		SR Consistency								
		Consistent				Inconsistent				
		RT		MT		RT		MT		I-C
Go Stimuli (60%)	No-Go Stimuli (40%)	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	RT
Experiment 1										
A white circle (on left or right)*	blank	281	13	81	10	292	14	81	10	11
B white circle (on left or right)*	two white circles	329	16	86	12	335	15	85	11	6
C green circle (on left or right)*	blank	288	13	82	10	295	13	86	12	7
D green circle (on left or right)*	red circle (on left or right)	322	15	85	12	331	15	83	11	9
E white arrow (pointing left or right)†	blank	302	14	89	15	303	14	84	10	1
F white arrow (pointing left or right)†	two-headed arrow	375	17	87	10	385	18	89	14	10
Experiment 2										
G H or M (on left or right)*	blank	289	14	87	11	299	16	85	10	10
H H or M (on left or right)*	N or W (on left or right)	455	21	111	11	447	23	111	10	−8

*Location of the stimulus is irrelevant to the go–no-go decision. †Direction of the arrow is irrelevant to the go–no-go decision.

rows, or the words *left/right*), which was very much dependent on the stimulus' being identified.

Some conditions in this experiment were similar to those in Hommel's (1995) Experiment 1, in which he asked subjects to press a key on the left or the right side. The particular response required on a trial was specified by a precue (three arrows) that was followed, 1 sec later, by a go or a no-go stimulus. The go (green light) and no-go (red light) stimuli appeared on either the left or the right; hence, its position was either on the same side as or on a different side from the response. His results showed that RT was faster when the location of the go stimulus and the response corresponded than when they did not (391 vs. 433 msec). However, Hommel (1995) did not look at the Simon effect with blank screens as no-go stimuli.

Method

Subjects

Twelve University of Michigan students were paid for their participation. They reported normal or corrected-to-normal vision and were right-handed, native English speakers between the ages of 19 and 25.

Design

We used a 3 × 2 × 2 × 2 design, with the within-subject factors of type of go stimulus, type of no-go stimulus, spatial consistency of the go stimulus with the response, and hand of response. Three types of go stimuli and two types of no-go stimuli were factorially combined to form six *blocked* conditions. These conditions are labeled A to F in Table 2. The go stimulus was a white circle that appeared on the left or the right of fixation (A and B), a green circle that appeared on the left or the right of fixation (C and D), or a white arrow that appeared at fixation but pointed to the left or the right (E and F). Each type of go stimulus carried spatial information, by virtue of either its spatial position (A to D), or its symbolic meaning[2] (E and F). Spatial information was irrelevant to the task, because the subjects were asked to execute the response to the go stimuli regardless of the spatial position of the circle or the direction of the arrow. A go stimulus appeared on 60% of the trials in a block, and a no-go stimulus appeared in the remaining 40% of the trials. In conditions A, C, and E, the no-go stimulus was a blank screen. Hence, in these conditions, simple detection of the go stimulus, regardless of its identity, was sufficient to determine that a go response should be executed. In conditions B, D, and F, on the other hand, the no-go stimuli were chosen so that some level of stimulus identification was required to determine whether a go response should be made. The no-go stimuli were two white circles, one on each side of fixation (B), a red circle on the left or the right of fixation (D), or a two-headed arrow (with one head pointing left and the other pointing right) appearing at fixation (F).

In each of the six blocked conditions, the spatial attribute of the go stimuli was either consistent or inconsistent with the go response (left or right movement of the hand) that the subjects were required to make. On half of the trials in each condition, the subjects responded with the left hand. On the other half, they used the right hand.

Apparatus and Stimuli

The experiment was controlled by an IBM PC that generated stimulus displays and recorded responses in milliseconds. The stimuli were presented against a black background on a CRT screen (640 × 480 pixels). The sizes of the display items were as follows: the word LEFT, 3.5 cm wide × 0.8 cm high; the word RIGHT, 4.5 cm wide × 0.8 cm high; the circle stimuli, 1 cm in diameter; and the arrow head, 1.6 cm wide × 0.8 cm high. The viewing distance was 81 cm. When a stimulus appeared on one side of the screen, its distance from fixation was 3.8 cm (center to center).

The response was made on a Plexiglas response box placed on a table in front of the subject. The response box consisted of three buttons arranged horizontally in a row. The middle button was the *home* button that was to be pressed to start a trial. The buttons located on the left and right sides of the home button were the *response* buttons, which were to be pressed as soon as the subject saw a go stimulus. The buttons had tops that measured 5.7 cm in diameter. The center-to-center distance between a pair of buttons was 12.7 cm.

Procedure

The subjects were instructed to press and hold the home button with their fingers when they were ready to start a trial. One second after the home button was pressed, a precue (the word LEFT or RIGHT) appeared in the middle of the screen for a randomly determined duration of between 800 and 1,200 msec. This precue told the subjects which response button to press on that particular trial. But the subjects kept holding the home button until they saw a go stimulus, which followed the precue immediately. As soon as the subjects saw a go stimulus, they released the home button and *moved* their hand to press either the left or the right response button. In cases in which they saw a no-go stimulus or a blank screen, they kept holding the home button until 2.5 sec had elapsed. At the end of every trial, feedback regarding response accuracy and (on the go trials) speed appeared on the screen for 1 sec. The subjects pressed the home button again when they felt ready to start the next trial. They were given several breaks during the experiment.

The experiment was divided into two sessions that were run on consecutive days. The subjects responded with their left hand in one session and with their right hand in the other session. Six subjects used the left hand in the first session, and the other 6 used the right hand. Each session began with a practice block, in which the subjects were trained to move their hands from the home button to the response buttons without looking. In this block, they responded only to a white circle at the center of the screen. This block was followed by another 18 blocks, 3 blocks for each combination of go and no-go stimuli (i.e., six conditions), as was described in the Design section. The subjects finished all 3 blocks of a condition before moving to the next. The 1st block in each condition was considered practice. The order of the conditions was different for each subject, and the order was reversed on the second session of the experiment. Each block consisted of 40 trials, 24 of which were go trials. They were divided equally into SR-consistent and SR-inconsistent trials.

Because a response was required on the go trials only, response latency here refers to those recorded on the go trials. There were two measures of response latency: RT, which was measured from the onset of a go stimulus to the release of the home button, and movement time (MT), which was measured from the release of the home button to the response button's being pressed. Response errors were recorded on both go (i.e., hand movement to the wrong side) and no-go (i.e., false alarms) trials.

Data Analysis

We excluded the following data from the analysis of response latency: the first trial of each block, the trial on which subjects made an error (e.g., hand movement to the incorrect side), and the trial immediately following error. The remaining data were then trimmed with the following procedure. First, we truncated the top and bottom 10% of the RT distribution for each condition by subject. On the basis of the mean and the standard deviation of this truncated set, we included all the data points of the complete data set (i.e., before truncation) that were within 3.3 standard deviations of that mean.

Results

For RT and MT, only the go trials, but not the no-go trials, were analyzed, because any responses on the no-go trials were errors. Of these, 6.9% of the RT and 5.4% of the MT data were trimmed with the procedure outlined above. Preliminary analysis indicated that the hand of response did not have any significant main or interaction effects. This factor was, therefore, dropped from further analyses. The average RT and MT for each condition are shown in Table 2. These data were analyzed with a 3 × 2 × 2 analysis of variance (ANOVA), with the within-subject factors of type of go stimulus (white circle, red circle, and white arrow), type of no-go stimulus (blank vs. noise), and spatial correspondence of go stimulus and response (consistent vs. inconsistent).

Reaction Time

On average, RT for the consistent trials was 7 msec faster than that for the inconsistent trials [$F(1,11) = 26.18$, $p < .001$]. The main effect of type of go stimuli was significant [$F(2,22) = 66.93$, $p < .001$]. RT to the circles (conditions A–D) was 32 msec faster than that to the arrows (conditions E and F). The main effect of type of no-go stimuli was also significant [$F(1,11) = 28.50$, $p < .001$].[3] RT was 54 msec faster when the no-go stimuli were blank than when they were similar to the go stimuli. The interaction of the types of go and no-go stimuli was significant [$F(2,22) = 30.92$, $p < .001$]. None of the other interaction effects was significant (Fs < 2.3, $p > .1$).

Because in conditions A–D, the spatial attribute of a go stimulus was its actual location (i.e., a circle located on the left or the right), whereas in conditions E and F, the spatial attribute of a go stimulus was its symbolic meaning (i.e., an arrow pointing left or right), additional statistical analyses were done separately for conditions A–D and E–F.

Conditions A–D. There was a significant main effect of SR consistency [$F(1,11) = 12.07$, $p < .01$] and of type of no-go stimuli [$F(1,11) = 250.70$, $p < .001$]. However, type of go stimuli (i.e., white vs. green circles) did not have a significant effect [$F(1,11) < 1$, $p > .5$]. The interaction of the types of go and no-go stimuli was marginally significant [$F(1,11) = 4.42$, $p < .06$]. None of the other interactions was significant [$F(1,11) < 1.2$, $p > .3$]. In conditions A and C, detection of a go stimulus was sufficient for a go decision, whereas in conditions B and D, some identification of the go stimulus was required. Hence, these two sets of conditions were analyzed separately for SRC effects. The results show that SRC effects were significant both when data from conditions A and C are pooled [$t(11) = 2.62$, $p < .05$], and when data from conditions B and D are pooled [$t(11) = 3.02$, $p < .05$].

Conditions E–F. The main effect of type of no-go stimuli was highly significant [$F(1,11) = 184.74$, $p < .001$]. However, the main effect of SR consistency was only marginally significant [$F(1,11) = 3.41$, $p < .1$], and so was the interaction of SR consistency and type of no-go stimuli [$F(1,11) = 4.52$, $p < .06$]. Pairwise t tests showed that SR consistency was significant in condition F, in which the no-go stimuli were double-headed arrows [$t(11) = 2,21$, $p < .05$], but not in condition E, in which the no-go stimuli were blanks [$t(11) = 0.14$, $p > .5$].

Movement Time

The mean MTs are also shown in Table 2. Mean MT was not significantly affected by any of the independent variables or by their interactions.

Reaction Time + Movement Time

The analysis of total time (TT = RT + MT) showed a similar pattern to that shown by the analysis of RT, except that the variance of the data was larger. Mean TT was significantly affected by type of go stimuli [$F(2,22) = 38.56$, $p < .001$], type of no-go stimuli [$F(1,11) = 301.65$, $p < .001$], and their interaction [$F(2,22) = 16.76$, $p < .001$]. Mean TT was also significantly affected by SR consistency [$F(1,11) = 18.87$, $p < .01$]. All the other interaction effects failed to reach significance. Because the analysis of TT reveals results very similar to those of the analysis of RT, it appears that there was no micro tradeoff between RT and MT.

Error Rates

The 12 subjects together made a total of 17 errors, 14 of which were in the SR-inconsistent condition, 3 of which were in the consistent condition, and none were on the no-go trials (i.e., no false alarms). The error data were not analyzed with statistical tests, because most of the subjects did not make any errors in one or more conditions. It is sufficient for our purpose to note that the SR-consistent trials have both shorter RTs and lower error rates than do the SR-inconsistent trials. Thus, the SRC effects found in RT cannot be attributed to a speed–accuracy tradeoff.

Discussion

We found spatial SRC effects in go–no-go tasks in which the spatial feature of the go stimulus was irrelevant to the go–no-go decision. The effects are small, as compared with similar effects in choice tasks. However, they are statistically significant.

The subjects in our task were instructed to prepare the response even before a go (or a no-go) stimulus was presented. Assuming that they were able to prepare the response, it is difficult to explain the SRC effects in terms of delays in response selection. Instead, such effects are consistent with the view, proposed by the DO model, that SRC effects are the results of the interaction between automatic and controlled response processes. Furthermore, the spatial SRC effects were significant even when mere detection of a go stimulus was sufficient for a go decision, if the spatial information was provided by the location of the stimulus (conditions A and C), but not if the spatial information was provided symbolically (condition E). We believe that this is so because automatic response activation may be generated quickly or slowly, depending on the time required to process the stimulus information on which the automatic response is contingent.

Although our results are consistent with this speed of processing (localization vs. identification) account, we should also consider an alternative account based on attention shift (see, e.g., Nicoletti & Umiltà, 1994). The attention shift hypothesis was originally put forth to explain the Simon effects in choice RT. It suggests that, in the Simon task, presentation of a choice stimulus induces attention shift, which in turn gives rise to a spatial code. This spatial code, if different from the required response, would make response selection difficult. Extending this account to the present task, one might argue that attention shift caused by the location of a go stimulus (an exogenous cue) is fast, whereas attention shift caused by the meaning of a go stimulus (an endogenous cue) is slow. However, it is not clear how a spatial code would interfere with a go–no-go response (see Umiltà & Nicoletti, 1992).

Note that this attention shift account would seem to imply that the response precues themselves, the words *left* and *right*, which tell the subjects to which side their hands should move, would also induce attention shift. This idea was investigated in the next experiment.

Finally, our subjects' movement time was not significantly affected by SRC, suggesting that SRC may not affect the execution of a discrete response. This, of course, does not exclude the possibility that SRC may affect the execution of more dynamic action sequences that extend a longer time (see Michaels & Stins, 1997).

EXPERIMENT 2

Although the results of Experiment 1 are consistent with the DO model, they are open to at least one alternative interpretation. Recall that the word *left* or *right* was used as a precue to specify the direction of the go response. Following the precue 1 sec later was a go stimulus (or a no-go stimulus) that appeared unpredictably on the left or on the right. RT to the go stimulus was shorter if the location of the go stimulus corresponded with the response side than if it did not. However, because the precue was confounded with the response side, logically, one could argue that the so-called SR consistency effects were, in fact, caused by the correspondence between the precue and the location of the go stimulus. This logical possibility also has an empirical basis. Previous research has shown that a precue that specifies the location of a target reduces RT (e.g., Posner, 1980). It is commonly believed that a spatial precue directs spatial attention to a cued location and facilitates the response to whatever object appears at that location. Because the sequence of stimulus events used in Experiment 1 is very similar to what is typically used in spatial precuing experiments, the precue that specified the go response might have directed attention (or eye movements) to the corresponding location and, hence, improved the speed of responding to any go stimulus that appeared at that location. This alternative interpretation is also applicable to Hommel's (1995, Experiment 1) results.

Fortunately, the DO model differs sufficiently from the spatial-precuing hypothesis to generate very different predictions. As was stated in the introduction, the DO model implies that the occurrence of SRC effects is dependent on the temporal overlap of a go decision and an automatic response. In Experiment 1, we showed that if the automatic response begins too late, relative to the go decision, there are no SRC effects. Similarly, we predicted that if the go decision is too slow, relative to the automatic response, there would not be SRC effects, either. The activation of an automatic response is usually assumed to be transient. If a go decision is delayed by a sufficient amount of time, the activation of the automatic response might dissipate and would cease to affect the response.

Although the go–no-go decisions in conditions B and D in the previous experiment, in which the no-go stimuli were somewhat similar to the go stimuli, were delayed significantly (as indicated in the slower go RT), as compared with conditions in which the no-go stimuli were blanks, they apparently were not delayed enough to eliminate the SRC effects caused by the spatial location of the go stimuli. In this experiment, we attempted to delay the go–no-go decision even more by making the discrimination of the go and no-go stimuli quite difficult. We used, as go and no-go stimuli, letters that are perceptually similar. If the DO model is correct, then as the go decision becomes sufficiently slow, the go RT could be unaffected by SRC.

On the other hand, if the SRC effects observed in Experiment 1 were due to spatial precuing, there is no reason that these effects should diminish as discrimination of the go and no-go stimuli becomes difficult. In a recent study, Johnston, McCann, and Remington (1995) found that spatial precuing effects were the same regardless of whether the letters to be discriminated were intact (easy discrimination) or distorted (difficult discrimination). There is even evidence that, in some conditions, the effects of spatial precuing may be more prominent when the target stimuli are degraded. For example, spatial-precuing effects have been found to increase with stimulus eccentricity and to decrease with stimulus exposure duration in discrimination tasks (Van der Heijden, Neerincx, & Wolters, 1989; Van der Heijden, Wolters, Groep, & Hagenaar, 1987). Spatial-precuing effects also increase with luminance decrement in detection tasks (Hawkins, Shafto, & Richardson, 1988). On the theoretical side, several popular accounts of spatial-precuing effects (e.g., Eriksen & St. James, 1986; LaBerge & Brown, 1989) have proposed that spatial precuing enhances perception of a cued stimulus (but see Shiu & Pashler, 1994, for contrary evidence). These theories would predict that perceptual enhancement is most useful when it is needed most—namely, when the differences among the stimuli to be discriminated are small. Therefore, if the SRC effects observed in Experiment 1 were some kind of spatial-precuing effects, they should not diminish, but might even increase, when the perceptual discrimination of go and no-go stimuli is difficult.

Method

The task and procedure of this experiment were similar to those of Experiment 1. The subjects moved their hand left or right from a home button when they saw a go stimulus, and they refrained from responding when they saw a no-go stimulus or a blank screen. The response to be made on a trial was cued by the same words (*left* or *right*) as those used in Experiment 1. The only changes were the go and no-go stimuli. The go stimuli were the letters H and M and the no-go stimuli were either a blank screen (condition G in Table 2) or the letters N and W (condition H). These letters were chosen so that a comparison with Kornblum and Zhang (1995) could be made (Table 1). The letters (go and no-go stimuli) appeared equally often on the left or the right of fixation. Hence, the position of a go stimulus was either consistent or inconsistent with the go response, although position was irrelevant to, and had no correlation with, the go–no-go decision. In the blank condition, mere detection of a stimulus was sufficient for the decision to go, whereas in the letter condition, a go stimulus had to be identified to the extent that it was categorized as H or M, rather than as N or W.

Because the hand of response did not have significant effects on the results of Experiment 1, the subjects in this experiment used the right hand for response. The independent variables in this experiment were no-go stimulus (blank vs. N/W) and SR consistency (consistent vs. inconsistent). The no-go stimulus condition was a between-subjects factor.[4] Eighteen subjects from the University of Michigan were equally divided between the two no-go stimulus conditions.

At the beginning of the experiment, the subjects were given 20 practice trials, with the go and no-go stimuli (or blanks) appearing at the center of the screen. This practice had two purposes. First, it was to enable them to learn to move their hands to the left or the right button without looking. Second, it was to ensure that they knew that the go–no-go decision was based on the identity of the stimuli (or the onset of the stimuli, in the case of blanks). Then the subjects had another 40 practice trials (60% go trials) in which the stimuli were randomly presented on the left or the right. They were reminded that location of the stimuli was irrelevant to the go–no-go decision. The experiment proper consisted of six blocks of 40 trials, 60% of which were go trials. The go trials were equally divided into consistent and inconsistent trials, with the letter H or M appearing on half of each. Likewise, on the no-go trials, the subjects saw either a blank screen (condition G) or the letters N and M, each on half of the trials (condition H). The no-go letters were also equally likely to be on the left or the right side of the screen. Thus, their locations were either consistent or inconsistent with the required response. Although no response should be made on these trials, a false response might be more likely when the no-go stimulus appeared on the side to which the hand was prepared to move.

Results

As for Experiment 1, response latencies recorded on the go trials, but not on the no-go trials, were analyzed, because any response on the no-go trials was an error. The RT and MT data, shown in Table 2, were subjected to the trimming procedure described for Experiment 1. About 3.9% of the RT and 4.7% of the MT data were trimmed.

Reaction Time

The mean RT for the SR-consistent and SR-inconsistent conditions were 289 and 299 msec, respectively, when the no-go stimuli were blank screens, and 455 and 447 msec, respectively, when the no-go stimuli were letters. The difference between the two no-go stimulus conditions was highly significant [$F(1,16) = 251.17$, $p < .001$], and so was its interaction with SR consistency [$F(1,16) = 11.78$, $p < .005$]. The main effect of SR consistency, however, was not significant [$F(1,16) < 1$]. Pairwise t tests show that the effect of SR consistency was significant only in the blank condition [$t(8) = 2.87$, $p < .05$], but not in the letter condition [$t(8) = 1.99$, $p = .08$]. In short, the go response was significantly affected by SR consistency when the go response was relatively fast (less than 300 msec), but not when it was relatively slow (about 450 msec).[5]

Movement Time

The average MT for the SR-consistent and inconsistent conditions were 87 and 85 msec, respectively, for the blank condition, and 111 and 111 msec, respectively, for the letter condition. The difference between the no-go stimulus conditions was marginally significant [$F(1,16) = 3.83$, $p < .07$]. Neither SR consistency nor its interaction with no-go stimulus conditions had significant effects on MT [$F(1,16) = 0.77$ and 1.60].

Reaction Time + Movement Time

The analysis of TT (RT + MT) shows a similar pattern to that of the analysis of RT. Mean TT was significantly affected by the type of no-go stimuli [380 vs. 562 msec; $F(1,16) = 10.64$, $p < .01$] and by the interaction of type of no-go stimuli and SR consistency [$F(1,16) = 10.64$, $p < .01$], but not by SR consistency [471 vs. 471 msec; $F(1,16) = 1.15$, $p > .05$]. Pairwise t tests show that the SR consistency effect was significant when the no-go stimuli were blanks [376 vs. 384 msec; $t(8) = 3.01$, $p < .05$], but not when the no-go stimuli were letters (566 vs. 558 msec; $t(8) = 1.64$, $p > .05$]. Because the analysis of TT reveals results that are very similar to those of the analysis of RT, there was no evidence of a micro tradeoff between RT and MT.

Error Rates

Overall, the error rates were low. When the no-go stimuli were blank screens, the average error rates were 0.3%, 1.7%, and 3% for the consistent, inconsistent, and no-go trials, respectively. When the no-go stimuli were letters, the average error rates were 0.6%, 1.1%, and 7.6% for the consistent, inconsistent, and no-go trials, respectively. In short, the subjects made the fewest errors in the SR-consistent condition and the most errors (false alarms) when the no-go stimuli looked like the go stimuli. The error data were not analyzed with statistical tests, because most of the subjects did not make any errors in one or more conditions. We note that the SR-consistent trials had both shorter RT and lower error rates than the SR-inconsistent trials. Thus, the SRC effects found in RT cannot be due to a speed–accuracy tradeoff.

Discussion

The results clearly show that SRC effects caused by irrelevant stimulus location in go–no-go tasks depend on how fast a go decision is reached. When the go decision was made on the basis of stimulus detection, the go response was fast (averaged less than 300 msec) and was significantly affected by whether the location of the go stimulus matched the response side. When the go decision required identifying and distinguishing the go stimulus from two visually similar no-go stimuli, the go response was relatively slow (averaged about 450 msec) and was hardly affected by SR consistency. These results confirm our general hypothesis that SRC effects owing to the location of a stimulus are attributable to an automatic process that is fast and temporally transient. They also disconfirm the alternative explanation that the SRC effects may be attributed to spatial precuing.

In contrast to the results of the present study, very different results were obtained by Kornblum and Zhang (1995; see Table 1) in what appears to have been the same task and with, seemingly, the same stimulus manipulations. Recall that, in their study, the stimuli were letters (the same as those used in our experiment), and the responses were letter names. They found SRC effects that were contingent on the go stimulus' being identified, which they had to be when the no-go stimuli were letters; they also failed to find SRC effects when the no-go stimuli were blanks, so that the go stimuli merely had to be detected. This, we believe, is because, when the automatic response (i.e., producing the letter name) was contingent on stimulus identification (i.e., with letters as no-go stimuli), its onset was too late to affect the fast go response that was triggered by stimulus detection.

As in Experiment 1, MT was not affected by SR consistency at all. However, MT in the letters condition (111 msec) was slower than that in the blank condition (86 msec), although the difference is only marginally significant. Such a difference was not found in Experiment 1. The discrepancy might be attributed to a difference in design. In the first experiment, all the conditions were within-subjects, whereas in the present experiment, the no-go stimulus condition was between-subjects.

GENERAL DISCUSSION

In two experiments, we found that when subjects were required to make a lateralized hand movement in response to a go stimulus, their RT was significantly affected by whether or not the spatial attribute of that go stimulus was consistent or inconsistent with the side of the response, even though the response side was known well in advance of the stimulus and the spatial attribute of the stimulus was irrelevant to the go–no-go decision.[6] Furthermore, our results show a remarkable difference between SRC effects caused by stimulus location and those caused by stimulus meaning. The location of a go stimulus produced SRC effects even when mere detection of that stimulus was sufficient for making the go decision; in contrast, when the spatial information in the stimulus was conveyed symbolically, SRC effects were obtained only when stimulus identification was required for making a go decision (Experiment 1). This strongly suggests that SRC effects can be mediated by an automatically activated response triggered either by a fast stimulus localization process or by a slow stimulus identification process. Only an automatic response that is triggered early is capable of affecting a go response that, in turn, is fast because of being triggered by stimulus detection.

Temporal Overlap of Automatic and Controlled Response Activations

When considered in the framework of the DO model, our results suggest that the automatic and the controlled response activation functions need to overlap in time in a highly specific way in order to produce SRC effects (Hommel, 1993a, 1994; Kornblum et al., 1999). In Experiment 1 (condition E), there were no significant SRC effects when the onset of the automatically activated response occurred too late (with symbolic spatial information), with respect to the onset of a fast go–no-go decision triggered by stimulus detection. In Experiment 2, there were no significant SRC effects either, when the onset of the automatically activated response occurred too early (with actual stimulus position), with respect to the onset of a slow, go–no-go decision triggered by stimulus identification. In contrast, significant SRC effects were found when the automatically activated response and the go–no-go decision were both fast (conditions A and C in Experiment 1 and condition G in Experiment 2) or both slow (condition F in Experiment 1).

The importance of temporal overlap between automatic and controlled response processes for producing SRC effects has been documented in choice RT studies (e.g., Hommel, 1993a). The present study extends the results to go–no-go tasks and illustrates a new way of controlling the temporal overlap. Many previous studies varied either the onset asynchrony of the relevant and irrelevant stimuli or the perceptual quality of the stimuli, in order to control the overlap. Recently, in our laboratory, we have been manipulating the level of processing of the relevant stimulus as a way of controlling the overlap. This may constitute an important methodological development in the study of SRC.

Locus of the Effect

Donders suggested that go–no-go tasks (Donders's *c* reaction) do not involve response selection, because the response is determined and fully prepared before the go stimulus appears. If this were the case, the SRC effects found in the present experiments could not have been caused by response selection processes. However, Donders' view has been challenged. It is quite clear that go–no-go tasks still involve some decision process: When a stimulus is presented, a decision must be made regarding whether to respond or not. The extent to which this constitutes a kind of *response selection* is unclear. Yet, given the copious literature on motor preparation, it would be unreasonable to claim that no preparation for the response can be made at all until a go decision has been reached (see, e.g., Rosenbaum, 1980; Sternberg, Monsell, Knoll, & Wright, 1978). Such evidence indicates that some response preparation is achieved during the interval between a response precue and a go stimulus.

One might argue that subjects "load" the go response and then, on go trials, simply initiate and execute that response, whereas on no-go trials they *select* an inhibitory response (cf. Pashler, 1994). Granted that this is a plausible argument, it does not place the SRC effects that we found in our experiments at the response selection stage, because those effects were found on the go trials, where, presumably, there was no response selection. If the go response had been "loaded" and was only waiting to be initiated, perhaps it is the response initiation process that is affected by SRC. That is, perhaps a "loaded" response can be initiated more quickly if the release stimulus (i.e., the go stimulus) is consistent with it than if it is not. Furthermore, because movement time was not affected by SRC, this limits the possible loci of the SRC effects (on RT) to processing stages before response execution. Response initiation seems to be a very plausible candidate.

Response Uncertainty

In our experiments, a go stimulus occurred on only 60% of the trials. Even though there is little uncertainty as to what the response was (because the response was precued), there was some uncertainty regarding whether the response should be executed. Is such uncertainty a necessary condition for obtaining SRC effects?

A recent study by Hommel (1996) suggests that such uncertainty is not required. In the first experiment of his study, Hommel used a task in which the correct response (a left or a right keypress) was precued on every trial, but the subjects had to withhold the response until a go stimulus appeared. Because a go stimulus appeared on every trial, this task was very close to a simple RT task. The only difference was that the required response changed from trial to trial. Hommel found that RT was significantly faster if the location of the go stimulus corresponded to the location of the response than if it did not (265 vs. 296 msec), which suggests that response uncertainty, in the sense of whether or not a response should be produced, is not necessary for obtaining SRC effects. Of course, this conclusion is valid only to the extent that Hommel's results were not contaminated by spatial-precuing effects, as was discussed above.

However, these results may still fall short of putting an end to the discussion of response uncertainty. It is still possible that, in the complete absence of any response uncertainty, SRC effects would not be obtained. In both Hommel's and our experiments, there was always more than one response that the subjects could make throughout an experiment. For example, in our experiments, the response to be made on a trial was either left or right and was determined randomly and precued. Although there was only one correct response on a trial basis, there were two correct responses on a block basis. If our go–no-go task were modified so that the response was fixed for a block of trials and a go stimulus appeared on every trial, the spatial correspondence of the go stimulus and the response might not affect RT. Some of Hommel's (1996, Experiment 3) results suggest that this might be the case.

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NOTES

1. Although Broadbent and Gregory (1962) called this condition incompatible, it is neutral in accordance with our taxonomy, because there is no conceptual relationship between *deck* and *bid* or *did*.

2. We note that the location of an arrow head, which is slightly off to one side of fixation, might also provide some spatial information.

3. The effect of a no-go stimulus refers to the effect of using a particular no-go stimulus in a block on the go responses in that block.

4. In a pilot experiment, the no-go stimulus condition was run as a within-subjects factor. However, the subjects made many false alarms when the no-go stimuli were letters, particularly when these letters appeared on the side to which they were supposed to move their hands, had the letter been a go stimulus. The subjects found it difficult to refrain from responding to these no-go stimuli, because they were used to responding to the onset of any stimuli in those blocks in which blank screens were the no-go stimuli. The number of false alarms decreased substantially when the two no-go stimuli conditions were given to different subjects.

5 At long RT, the direction of SRC effects reversed, although not significantly so. See Zhang and Kornblum (1997) for an interpretation of similar findings.

6. We believe that these are genuine spatial SRC effects that are not attributable to interhemispheric transmission time. There is evidence that simple RT is shorter if a stimulus appears in the visual hemifield that projects directly to the cerebral hemisphere that controls the effector of response (e.g., left visual field–right hemisphere–left hand) than if it appears in the other visual hemifield (Bashore, 1981). However, this does not explain our results, because the subjects used only one hand to make the left or the right movement.

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