

The Simon task with multi-component responses: two loci of response–effect compatibility

Motonori Yamaguchi · Robert W. Proctor

Received: 23 April 2010 / Accepted: 30 June 2010 / Published online: 13 July 2010
© Springer-Verlag 2010

Abstract The stimulus–response compatibility (SRC) effect refers to the phenomenon that responses are faster and more accurate when stimulus and response correspond than when they do not. The phenomenon is robust in that it is observed even when SRC is irrelevant to performing the task, a variant known as the *Simon effect*. Recent studies also demonstrated that responses are faster when they are spatially compatible with their effects in the environment (action effects) than when they are incompatible. This *response–effect (R–E) compatibility effect* is thought to stem from the fact that stimuli first activate anticipated effect codes, which then activate corresponding action codes. In the present study, the Simon task was used to examine influences of multiple response components on performance. Three response components were orthogonally manipulated. The results of three experiments indicated that there are two separate processes that are influenced by R–E compatibility; one that is responsible for the SRC effect (S–R translation) and the other that is independent of SRC (action programming). The influence of R–E compatibility on the former process depended on manipulations that varied attentional demands of the task.

Introduction

The *stimulus–response compatibility (SRC)* effect refers to the fact that responses are faster and more accurate when stimuli and responses correspond than when they do not (see Proctor & Vu, 2006, for a review). For instance,

pressing keys is faster, and often more accurate, when responding to stimuli that are spatially compatible with key locations than when responding to stimuli that are spatially incompatible. The SRC effect can arise when there is similarity, or dimensional overlap, between stimuli and responses (Kornblum, Hasbroucq, & Osman, 1990), irrespective of whether it involves task-relevant or -irrelevant stimuli (Simon & Rudell, 1967). When the SRC effect emerges on the basis of S–R relationships that are not relevant to the task, the effect is called the *Simon effect* (cf. Lu & Proctor, 1995; Simon, 1990). For instance, participants may be told to respond to the color of visual stimuli by pressing left and right response keys. Even though the stimulus locations are not informative as to which response should be selected, responses are still faster when stimulus and response are spatially compatible than when they are incompatible.

The Simon task has been used to investigate a range of cognitive processes (Hommel, 2010) because it offers a useful tool to dissociate contributions of multiple factors in an operational context. For instance, in Simon, Hinrichs, and Craft's (1970) study, participants responded to the pitch of auditory stimuli that were presented to the left or right ears. In one condition, they performed with the normal hand placement (the left and right response keys were pressed, respectively, by the left and right index fingers); in the other condition, participants performed with a 'crossed hand' placement (the left and right response keys were pressed, respectively, by the right and left index fingers). With this hand-placement manipulation, Simon et al. were able to dissociate influence of the stimulus-hand correspondence from that of the stimulus-key correspondence and examine whether the responses were represented based on the locations of the response keys or the sides of their hands. Their results showed that the Simon effect emerged

M. Yamaguchi (✉) · R. W. Proctor
Department of Psychological Sciences, Purdue University,
703 Third Street, West Lafayette, IN 47907-2081, USA
e-mail: myamaguc@psych.purdue.edu

based on the stimulus-key correspondence, not the stimulus-hand correspondence, suggesting that the task context was represented with respect to the key locations. This finding was replicated by Wallace (1971, 1972) by using visual stimuli.

Also, Guiard (1983) conducted an experiment in which participants responded to auditory stimuli by steering a wheel to the left or right. In one condition, they were asked to hold the bottom of the steering wheel with both hands. With this hand placement, the directions of hand and wheel movements were dissociated, in that the hands moved in the opposite direction to the movement direction of the steering wheel. Results suggested that the Simon effect occurred according to the stimulus-hand correspondence for half the participants, but according to the stimulus-wheel correspondence for the other half. Guiard further introduced into the task a visual cursor whose movement was contingent on the steering wheel and found that the Simon effect always occurred according to the correspondence between the stimulus side and the cursor movement (see also Wang, Proctor, & Pick, 2007).

Similarly, in Hommel's (1993) study, left and right keypresses were followed by a flash of one of the two lights located on the left and right sides. Participants responded to the pitch of auditory stimuli presented from the left or right speaker. In critical conditions, left and right keypresses were followed by a flash of the right- and left-side lights, respectively, dissociating the stimulus-key (or -hand) correspondence from the stimulus-light correspondence. One group of participants was told to press the left or right key in response to the stimuli, but the other group was told to flash the left or right light. For the key-instruction group, the Simon effect was observed based on the stimulus-key correspondence, but for the light-instruction group, the effect was reversed so that the Simon effect was observed based on the stimulus-light correspondence.

The results of Guiard's (1983) and Hommel's (1993) studies are important for two reasons. First, they suggest that participants can represent a task context flexibly when there are multiple components that are associated with responses. The representation of a task context is influenced primarily by salient task features (such as cursor movement) and the task goal established by instructions. Second, that the Simon effect can occur based on the cursor motion or light location implies that response representation is not restricted to the physical properties of actions such as the direction of a wheel rotation or the location of a key. Instead, responses can be coded in terms of some distal effects of the actions, or *action effects*. In Guiard's experiment, action effects (cursor movements) were the major determinants of the task representations, whereas in Hommel's experiment, participants were able to intentionally switch between the response locations and action-

effect (flash of a light) locations to represent the task context according to given instructions.

In addition to SRC, recent studies demonstrated that compatibility between actions and action effects also influences task performance. Kunde (2001) had participants respond to the color of visual stimuli presented at the screen center by pressing one of four response keys. These response keys were associated with four visual effects whose location varied horizontally on the screen. He found that responses were faster when the locations of response key and visual effect corresponded than when they did not. Similarly, Kunde, Müsseler, and Heuer (2007) conducted an experiment in which participants were to move the tip of a computer-generated lever by moving a handle mounted in front of the screen. In one condition, the movement direction of handle (or that of the hand operating the handle) corresponded to the movement direction of the lever tip. In another condition, the tip moved in the opposite direction of that of handle movement. Responses were faster when the directions of the lever tip and the handle corresponded than when they did not, yielding the *response-effect* (R-E) *compatibility* (Kunde, 2001), or *hand-tool correspondence* (Kunde et al., 2007), effect.

Kunde et al.'s (2007) study suggested that the hand-tool correspondence (or R-E compatibility) was independent of the stimulus-tool correspondence effect (i.e., the Simon effect). That is, responses were faster when the lever tip was moved toward the stimulus location than when it was moved away from the stimulus location, but this advantage of the 'moving-toward' trials (i.e., S-R compatible trials) was as large for the hand-tool (R-E) incompatible condition as for the hand-tool (R-E) compatible condition. The outcomes are consistent with Simon et al.'s (1970) study in which responses were faster for the hand-uncrossed condition than for the hand-crossed condition, but the size of the Simon effect was comparable between these conditions (see also Guiard, 1983; Wallace, 1971, 1972). These observations suggest that the cognitive processes responsible for the R-E compatibility effect are independent of the processes responsible for the Simon effect and that a single response component dominates the Simon effect.

However, the aforementioned study of Hommel (1993, Experiment 2) orthogonally manipulated the stimulus-hand, -light, and -key correspondences and found that these relations additively produced the Simon effect. In other words, when computed with respect to the correspondence between stimulus and light locations, the Simon effect was larger, for example, when the locations of key and light corresponded (R-E compatible condition) than when they did not (R-E incompatible condition), because stimulus-key and -light correspondences were consistent in the former condition but were inconsistent in the latter. Thus, the results of Hommel's study suggested that the processes

responsible for the SRC effect are affected by R–E compatibility and that multiple response components can simultaneously produce the Simon effect. To date, the reason for this discrepancy remains unknown.

Present study

Three experiments were conducted to investigate the processes underlying the SRC effect (Simon effect) and the R–E compatibility effect. The experiments consisted of a choice-reaction task in which participants controlled a simulated aircraft by operating a flight yoke (Yamaguchi & Proctor, 2006, 2010). In the task, they were presented with left and right stimuli on each trial, for which the stimulus locations were task-irrelevant, and banked the aircraft to the left or right according to a pre-specified stimulus dimension. The attitude (roll) of the aircraft was presented through the attitude indicator displayed on the computer monitor (see Fig. 1). The advantage of using this task condition is the involvement of multiple response components that are dissociable in the experiments.

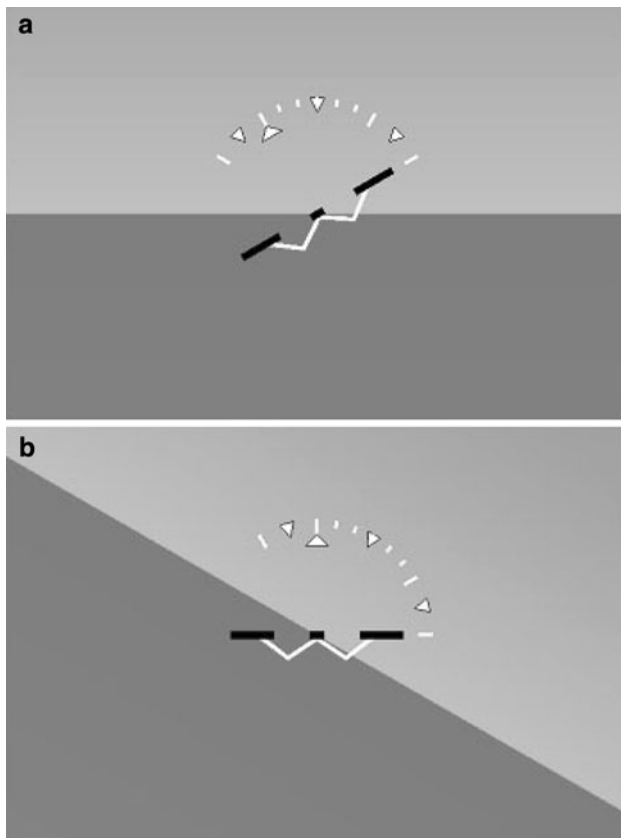


Fig. 1 The aircraft-move and horizon-move formats of the attitude indicator used in the present experiments: **a** aircraft-moving, **b** horizon-moving

Three factors were of particular interest; the movement directions of the aircraft, display symbols, and the hands that operated the flight yoke. The last factor is the physical action that participants take in response to stimuli, and the former two factors are the effects of that action (action effects). Two experimental variables were manipulated to dissociate the influences of these response factors on task performance. The first variable was the display format of the attitude indicator. The format of the indicator was *aircraft-moving* (see Fig. 1a) for one group of participants and *horizon-moving* (see Fig. 1b) for the other group in each experiment. The second variable was the control relation between the aircraft and hands. In the *normal-control* condition, the direction of the simulated aircraft's movement corresponded to the direction of the control movement (e.g., turning the flight yoke to the left resulted in banking of the aircraft to the left). In the *reverse-control* condition, the direction of the aircraft movement was opposite to the direction of the control movement (e.g., turning the flight yoke to the left resulted in banking of the aircraft to the right).

Note that when the display format is aircraft-moving, the physical movement direction of display object (aircraft-symbol) is consistent with that of the simulated aircraft, whereas when the display format is horizon-moving, the physical movement direction of display object (artificial horizon) is inconsistent with that of the simulated aircraft. At the same time, in the normal-control condition, the directions of hand and aircraft movements are consistent, whereas in the reverse-control condition, they are inconsistent. Consequently, for each of the left and right stimulus locations, there were eight compatibility relations that were created by the combinations of the two display formats and the two control relations (see Table 1).

As can be seen in Table 1, for the aircraft-moving format with the normal-control condition (the first and second columns; Conditions 1 and 2), the movements of aircraft, display, and hand were all consistent. When the stimulus location was compatible with the direction of aircraft movement, it was also compatible with other two factors (Condition 1), but when the stimulus location was incompatible with the aircraft movement, it was incompatible with other two factors (Condition 2). In contrast, for the aircraft-moving format with the reverse-control condition (the third and fourth columns; Conditions 3 and 4), the movement of the aircraft was consistent with the display movement, but it was inconsistent with the hand movement. Thus, when the stimulus location was compatible with the direction of aircraft movement, it was also compatible with the display movement but incompatible with the hand movement (Condition 3), but when the stimulus location was incompatible with the aircraft movement, it was incompatible with the display movement but compatible with the hand movement (Condition 4). Therefore, any

Table 1 Compatibility relations between stimulus location and three response components: movement directions of simulated aircraft, display symbol, and hands

	Aircraft-move				Horizon-move			
	Normal-control		Reverse-control		Normal-control		Reverse-control	
Condition	1	2	3	4	5	6	7	8
Stimulus-aircraft ^a	+	–	+	–	+	–	+	–
Stimulus-display	+	–	+	–	–	+	–	+
Stimulus-hand	+	–	–	+	+	–	–	+

Positive sign, compatible; negative sign, incompatible

^a The Simon effect was defined in terms of the compatibility between the stimulus location and the direction of aircraft movement: Conditions 1, 3, 5, and 7, were the ‘compatible’ trials, and Conditions 2, 4, 6, and 8, were the ‘incompatible’ trials. The Simon effect was computed by subtracting RT (or PE) of the compatible trials from RT (or PE) of the incompatible trials

differences in the Simon effect between the two conditions (Condition 2–Condition 1 vs. Condition 4–Condition 3) should imply a contribution of hand movement to the choice-reaction performance. In the same manner, the factorial combinations of the two display formats and the two control relations provided all conditions that were necessary to isolate the influences of the three response components.

Throughout the remainder of the article, the Simon effect is defined with respect to compatibility between the stimulus location and the movement direction of the aircraft, because participants were instructed on their task in terms of aircraft movement. Consequently, the ‘compatible trials’ were those in which the correct direction of the aircraft was toward the stimulus location (Conditions 1, 3, 5, 7), whereas the ‘incompatible trials’ were those in which the correct direction of the aircraft was away from the stimulus location (Conditions 2, 4, 6, 8).

The central issue is whether R–E compatibility has the same locus in the cognitive processes as SRC (the Simon effect) and whether the Simon effect can be produced simultaneously by multiple response components. In Kunde et al.’s (2007) study, responses were faster for the R–E compatible trials than for the R–E incompatible trials, but the Simon effect (as computed with respect to the stimulus-effect correspondence) was comparable between these trial conditions. The result suggests that the locus of the R–E compatibility effect is independent of that for the Simon effect and that the Simon effect was determined by a single response component. However, in Hommel’s (1993) study, the Simon effect was larger for the R–E compatible trials than for the R–E incompatible trials, suggesting that R–E compatibility influences cognitive processes responsible for the Simon effect and that the Simon effect is determined by multiple response components. In both studies, R–E compatibility was created based on the locations of participants’ hands and visual action effects. However, the imperative stimuli were auditory tones in

Hommel’s study, whereas they were visual signals in Kunde et al.’s study. Also, in Hommel’s study, responses were discrete keypresses, whereas in Kunde et al.’s study, they were continuous movement of a lever to a target position.

Therefore, across the three experiments of the present study, stimulus modality and response mode were manipulated. In Experiment 1, the imperative stimuli were auditory as in Hommel’s (1993) study, but they were visual in Experiment 2 as in Kunde et al.’s (2007) study. In these experiments, participants were instructed only to bank the aircraft to the left or right. While using the same visual stimuli as in Experiment 2, Experiment 3 required participants to bank the aircraft to a specific target position and maintain that attitude for 1 s. Hence, in the former two experiments, participants’ responses were rather ballistic (discrete) in that, once responses were initiated, participants did not need to be concerned about the attitude of the aircraft. In the latter experiment, however, responses were continuous in that finer control of the aircraft’s attitude was required until the trial was terminated. These manipulations allow examining the discrepancy between Kunde et al.’s and Hommel’s studies. If Kunde et al.’s results can be replicated, that finding would indicate that there is an R–E compatibility effect that is independent of the SRC effect. But, if R–E compatibility influences the Simon effect, it would indicate that there is an R–E compatibility effect that affects the processes that are responsible for the SRC effect.

Experiment 1

In this experiment, participants turned a simulated aircraft to the left or right in response to the pitch of auditory stimuli, presented in the left or right ear, by operating a flight yoke. As described earlier, the display format and the control relation between the yoke and the aircraft were

manipulated, creating eight trial conditions summarized in Table 1. In terms of the conventional analysis of variance (ANOVA), the main effect of compatibility corresponds to the influence of the aircraft movement, because the Simon effect was computed with respect to the compatibility between the stimulus location and the direction of aircraft movement. The influences of display and hand movements are indicated by the interaction of compatibility with display format and control relation, respectively. That is, if the display movement influences the Simon effect, the effect should be reduced when the stimulus location is incompatible with the direction of the display movement even if it is compatible with other factors. Consequently, the Simon effect should be larger for the aircraft-move display than for the horizon-move display, resulting in the interaction between compatibility and display format. A similar reasoning is applied to the influence of hand movement; if it is significant, compatibility should interact with control relation.

If the Simon effect is determined by a single response component (e.g., Guiard, 1983; Kunde et al., 2007; Simon et al., 1970; Wallace, 1971), only one of the aforementioned effects would be significant. On the other hand, if multiple response components can produce the Simon effect at the same time (Hommel, 1993), more than one effect should be significant. Furthermore, as Kunde et al. (2007) found in their study, we expected that responses would be faster for the normal- than for the reverse-control condition, resulting in the R–E compatibility effect. Also, there is a possibility that the R–E compatibility effect is obtained based on the relation between the movements of display and hands. That is, with the normal-control, responses may be faster for the aircraft-move display than for the horizon-move display because the display movement is consistent with the hand movement in the former but it is inconsistent in the latter. In contrast, with the reverse-control, responses may be faster for the horizon-move display than for the aircraft-move display because the display movement is now consistent with the hand movement for the former, but not for the latter. Such an effect should be reflected in the interaction between display format and control relation. Based on our previous studies (Yamaguchi & Proctor, 2006, 2010), however, this possibility is unlikely.

Method

Participants

Forty undergraduate students at Purdue University were recruited from the subject pool of introductory psychology courses. They received partial course credits for participation. All participants reported having normal or corrected-to-normal visual acuity and normal hearing. None had prior

training or education in aviation. Half the participants were randomly assigned to one of two experimental conditions (aircraft-move vs. horizon-move display conditions; see below). The mean and standard deviation of participants' ages were 19.10, and 1.07 for the aircraft-move condition and 19.25 and 1.83 for the horizon-move condition. There were nine females in the aircraft-move condition and seven females in the horizon-move condition.

Apparatus and stimuli

The apparatus consisted of a personal computer and a 19-in. VGA flat monitor. The experiment was controlled by a computer program constructed by Microsoft VisualBasic 6.0, which recorded response time (RT) to 1-ms accuracy. Responses were registered by turning a flight yoke. The yoke was situated in front of the computer monitor at a distance of 15 cm. The distance between the left and right grips was approximately 28 cm. The computer monitor presented an aircraft-attitude display (22 cm in width and 14.6 cm in height; see Fig. 1) against a black background. The display object at the center was the aircraft symbol composed of black and white rectangles. The bank markings were located above the aircraft symbol, which indicated the bank angle of the aircraft. The three isosceles triangles above the aircraft symbol represented the bank angles of 0° and 45° to the left and right, respectively. The upper region of the display background was colored in blue, and the lower region in brown; they represented the sky and the ground. The border line of the two regions represented an artificial horizon.

For one group of participants (*aircraft-move display group*), the bank markings and the artificial horizon were stationary, and the aircraft symbol rotated in clockwise or counterclockwise direction corresponding to the bank direction of the simulated aircraft (see Fig. 1a). For the other group of participants (*horizon-move display group*), the aircraft symbol was stationary at the center, and the bank markings and the artificial horizon rotated in the direction opposite to the bank direction of the aircraft (see Fig. 1b). Thus, with the normal control (i.e., when the aircraft movement corresponded to the hand movement), the display movement was compatible with the hand movement in the aircraft-move display, whereas it was incompatible in the horizon-move display. However, with the reverse control (i.e., when the aircraft movement did not correspond to the hand movement), the display movement was compatible with the hand movement in the horizon-move display, whereas it was incompatible in the aircraft-move display.

The imperative stimuli were high- and low-pitch tones presented through headphones, either to the left or right ear. The frequencies were, respectively, 880 and 440 Hz,

and the intensity was approximately 64 dB measured at the headphones.

Procedure

The experiment was conducted individually for each participant under normal florescent room lights. Participants sat in front of the computer screen at an unrestricted viewing distance of approximately 70 cm. They were instructed to hold the left and right grips of the flight yoke with their respective hands, place their thumbs on rests equipped on the grips, and wear headphones throughout the experiment. For each experiment, participants were randomly assigned to either of the two display groups (aircraft-move or horizon-move).

There were two blocks of 156 test trials for each participant, one for the *normal-control* condition and the other for the *reverse-control* condition. In the normal-control condition, turning the flight yoke caused the aircraft to turn in the corresponding direction. In the reverse-control condition, turning the flight yoke caused the aircraft to turn in the opposite direction. The order of these conditions was counterbalanced across participants. Throughout the session, the first-order control was used, meaning that the degree of yoke displacement corresponded to the velocity of the aircraft rotation (the greater the degree of displacement is, the faster the aircraft turns). Each test block was preceded by a block of 12 practice trials. The first 12 test trials were considered as warm-up and were not included in analysis. An experimental session lasted for less than 30 min for each participant.

At the beginning of the experimental session, the experimenter described the relevant display objects (aircraft symbol, bank markings, and artificial horizon) by presenting the display format to which participants were assigned. Then, they were asked to explore how the display changed according to inputs from the flight yoke. The normal control was used during this familiarization phase. After the familiarization phase, participants read written instructions presented on the screen, which described their tasks. Participants were asked to respond to stimuli as quickly and as accurately as they could. At this point, they were also informed that in one of the two trial blocks, the control would be reversed.

The aircraft was positioned at the bank angle of zero degrees at the beginning of each trial. Participants were instructed to keep the flight yoke at the neutral position before an onset of the imperative stimulus. If the yoke was kept at the appropriate position for 1,000 ms, the imperative stimulus was presented; whenever a displacement occurred before the stimulus onset, the counter was reset, and participants had to wait another 1,000 ms. A high- or low-pitch tone was presented in the left or right ear through

headphones. Half the participants responded to the high- and low-pitch tones by banking the aircraft to the left and right, respectively; the other half used the reversed mapping. The imperative stimulus was terminated, and the display was frozen when the aircraft's roll reached the bank angle of 45° to either direction. RT was the interval between stimulus onset and displacement of the flight yoke approximately 10° to the left or right. This response criterion was not explicit to participants. If participants turned the flight yoke beyond this response criterion in the incorrect direction, the response was recorded as an error. The message "ERROR" was presented above the attitude display, horizontally centered at the screen, for 500 ms when the aircraft was banked 45° to the incorrect direction. Note, however, that the error feedback was not given if the eventual bank direction was correct, even though the initial response direction was incorrect. No feedback was provided for correct responses. The aircraft symbol was automatically positioned back at the initial position as the flight yoke was reset at the neutral position, and the next trial started.

Results and discussion

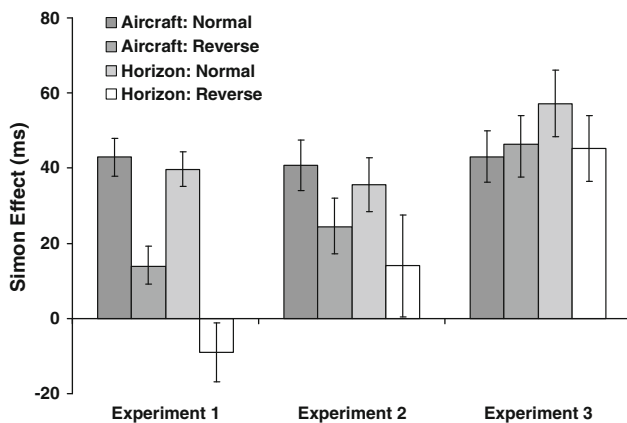
Mean RT for correct responses and percentage errors (PE) were computed for each participant for each experiment (see Table 2). Trials for which RT was <100 or >1,500 ms were discarded. The percentage of the discarded trials was 0.16%. RT and PE were submitted to ANOVA as a function of compatibility (compatible vs. incompatible; within-subject), control relation (normal vs. reverse; within-subject), and display format (aircraft-move vs. horizon-move; between-subject). Compatibility was coded with respect to the spatial relationship between the stimulus location and the movement direction of the simulated aircraft, based on which participants were instructed upon the task. The Simon effect was mean RT for the incompatible trials minus mean RT for the compatible trials (see Fig. 2).

For RT, there were main effects of Compatibility, $F(1, 38) = 57.76$, $MSE = 331$, $p < 0.001$, $\eta_p^2 = 0.603$, and Control Relation, $F(1, 38) = 6.25$, $MSE = 3,552$, $p < 0.017$, $\eta_p^2 = 0.141$. Responses were faster for the compatible trials ($M = 477$ ms) than for the incompatible trials ($M = 498$ ms), indicating a 21-ms Simon effect. Responses were also faster for the normal-control condition ($M = 476$ ms) than for the reverse-control condition ($M = 499$ ms), indicating the R–E compatibility effect based on the relation between the aircraft and hand movements. The main effect of Display Format was not significant, $F(1, 38) < 1$, $MSE = 21,824$, $\eta_p^2 = 0.004$. However, there was a significant interaction between Display Format and Compatibility, $F(1, 38) = 5.11$, $MSE = 331$, $p < 0.030$, $\eta_p^2 = 0.118$. The outcome reflects the fact that the Simon

Table 2 Mean response times (RT, in ms) and percentage errors (PE) for the aircraft-move and horizon-move displays as a function of control relation and compatibility

Control	Compatibility	RT		PE	
		Aircraft-move	Horizon-move	Aircraft-move	Horizon-move
Experiment 1					
Normal	Compatible	459 (16.34)	451 (19.31)	1.67 (0.47)	1.81 (0.43)
	Incompatible	502 (17.34)	491 (21.21)	7.65 (1.27)	8.20 (1.29)
Reverse	Compatible	496 (16.86)	500 (19.32)	7.53 (1.29)	6.12 (0.97)
	Incompatible	510 (17.22)	491 (16.20)	7.44 (1.28)	8.15 (1.14)
Experiment 2					
Normal	Compatible	484 (16.80)	527 (21.37)	2.58 (0.59)	1.50 (0.51)
	Incompatible	525 (15.83)	562 (22.17)	8.71 (1.40)	5.16 (0.86)
Reverse	Compatible	544 (17.57)	568 (20.39)	5.28 (1.05)	5.45 (0.84)
	Incompatible	568 (18.71)	582 (25.37)	5.78 (2.09)	5.78 (0.89)
Experiment 3					
Normal	Compatible	560 (21.16)	499 (15.65)	1.82 (0.42)	4.05 (1.22)
	Incompatible	603 (19.64)	557 (17.58)	4.05 (0.74)	8.30 (0.98)
Reverse	Compatible	631 (26.39)	581 (19.32)	7.30 (1.04)	6.94 (1.04)
	Incompatible	677 (24.81)	626 (19.32)	11.06 (1.53)	12.14 (1.69)

Values in parentheses are the standard errors of the mean

**Fig. 2** The Simon effect as a function of Display Format and Control Relation in Experiments 1–3 (error bars represent one standard error)

effect was larger for the aircraft-move format ($M = 28$ ms) than the horizon-move format ($M = 15$ ms). There was also a significant interaction between Compatibility and Control Relation, $F(1, 38) = 42.08$, $MSE = 360$, $p < 0.001$, $\eta_p^2 = 0.525$, which suggests that the Simon effect was larger for the normal-control condition ($M = 41$ ms) than for the reverse-control condition ($M = 2$ ms). The three-way interaction of the Display Format, Compatibility, and Control Relation was not significant, $F(1, 38) = 2.68$, $MSE = 360$, $\eta_p^2 = 0.066$.

For PE, the main effects of Compatibility, $F(1, 38) = 48.21$, $MSE = 10.62$, $p < 0.001$, $\eta_p^2 = 0.559$, and Control Relation, $F(1, 38) = 25.02$, $MSE = 9.81$, $p < 0.001$, $\eta_p^2 = 0.397$, were significant. They also interacted, $F(1, 38) = 19.78$, $MSE = 13.70$, $p < 0.001$, $\eta_p^2 = 0.342$, suggesting

that the Simon effect was larger for the normal-control condition ($M = 6.18\%$) than for the reverse-control condition ($M = 0.98\%$). Other effects were not significant.

The Simon effect was obtained with respect to the aircraft movement, display movement, and hand movement. There was no significant interaction that involved all three factors, implying little evidence for a violation of additivity of the response component effects in producing the Simon effect, which agrees with the results of Hommel's (1993) experiment. The results suggest that responses are represented in terms of multiple frames of reference, just as in the case of stimuli (e.g., Lamberts, Tavernier, & d'Ydewalle, 1992), and these multiple response components produce the Simon effect additively.

At the same time, responses were generally faster for the normal-control condition than for the reverse-control condition. This reflects the R–E compatibility effect based on the aircraft and hand movements, which is analogous to the effect observed in Kunde et al.'s (2007) experiment. On the other hand, there was no significant effect of R–E compatibility between the display and hand movements. This outcome is consistent with our previous studies (Yamaguchi & Proctor, 2006, 2010), according to which participants performed the task based on a mental model that represents the simulated aircraft rather than the physical display motion. Nevertheless, the fact that the Simon effect can also occur based on the compatibility between the stimulus location and the display movement implies that display motion was also a factor in representing responses. This appears contradictory to the lack of the display-hand

compatibility effect if one considers the S–R and R–E compatibility effects arise from the same mechanism, but not if different mechanisms are responsible for these effect. Thus, there is an indication of independent mechanisms that are responsible for the S–R and R–E compatibility effects. We will elaborate this point in “[General discussion](#)”.

Experiment 2

Experiment 1 demonstrated that the Simon effect can be produced simultaneously based on multiple response components. The results are consistent with previous studies that the Simon effect can emerge based on multiple stimulus codes (Lamberts et al., 1992; Lleras, Moore, & Mordkoff, 2004; Roswarski & Proctor, 1996). Thus, much as multiple reference frames can be adopted in representing a stimulus, responses can also be represented based on multiple reference frames (Hommel, 1993).

However, Kunde et al. (2007) tested the Simon task in a condition similar to Experiment 1. In their study, participants moved a lever handle (action) and controlled a computer-generated lever tip (action effect) to the left or right location. Also, the Simon effect was obtained based on the correspondence between the stimulus location and the direction of the action effect; the Simon effect was not obtained based on the correspondence between the stimulus location and the direction of the handle movement. That is, Kunde et al.’s task involved a single frame of reference even if responses consisted of multiple components.

A possible reason for the outcome is that participants responded to visual stimuli that appeared on the same display as the lever tip was presented. Consequently, attention was drawn toward the lever tip, which then dominated the Simon effect. If this is the case, Kunde et al.’s results imply that the Simon effect can be attentionally modulated. Note that the Simon effect is typically attributed to automatic, or unconditional, response activation (De Jong, Liang, & Lauber, 1994; Kornblum et al., 1990). Attentional modulation of the Simon effect undermines this automaticity explanation. To examine whether Kunde et al.’s results can be replicated, the present experiment used visual stimuli. Because the task condition was exactly the same as that of Experiment 1 in other respects, any influence of change in task contexts on the Simon effect implies that the process that underlies the effect is not strictly automatic.

Method

Participants

Forty undergraduate students were newly recruited from the same subject pool as in Experiment 1. None had

participated in Experiment 1. The mean and standard deviation of participants’ ages were 19.00 and 1.49 for the aircraft-move condition and 19.50 and 2.12 for the horizon-move condition. There were 10 females in the aircraft-move condition and 14 females in the horizon-move condition.

Apparatus, stimuli, and procedure

The apparatus and stimuli were the same as those used in Experiment 1, except that the imperative stimuli were green or red rectangles in the present experiment. The stimuli appeared just above the left or right upper corner of the attitude display. The width and height of the rectangles were 2.2 and 1.5 cm, respectively. For half the participants, a green rectangle was responded by moving the aircraft to the left, and a red rectangle was responded by moving the aircraft to the right; the mapping was reversed for the other half. For incorrect responses, an error tone (440 Hz) was presented binaurally through headphones, which lasted for 500 ms. Experiment 2 was identical with Experiment 1 in other respects.

Results and discussion

The data were analyzed in the same manner as in Experiment 1 (see Table 2). 0.76% of all trials were discarded for being outside the criteria.

For RT, there were main effects of Compatibility, $F(1, 38) = 32.63$, $MSE = 1,007$, $p < 0.001$, $\eta_p^2 = 0.462$, and Control Relation, $F(1, 38) = 21.26$, $MSE = 3,177$, $p < 0.001$, $\eta_p^2 = 0.359$. Responses were faster for the compatible trials ($M = 531$ ms) than for the incompatible trials ($M = 559$ ms), and for the normal-control ($M = 524$ ms) than for the reverse-control ($M = 566$ ms). The interaction between these factors was also significant, $F(1, 38) = 5.25$, $MSE = 682$, $p < 0.028$, $\eta_p^2 = 0.121$. These outcomes reflect the fact that the Simon effect was smaller for the reverse-control condition ($M = 19$ ms) than for the normal-control condition ($M = 38$ ms), consistent with Experiment 1. However, the interaction of Display Format and Compatibility was not significant, $F(1, 38) < 1$, $MSE = 1,007$, $\eta_p^2 = 0.016$, indicating that the Simon effect was comparable for the two display conditions (33 ms for the aircraft-move display, 25 ms for the horizon-move display). That is, in contrast to Experiment 1, there was little evidence of the influence of Display Format on the Simon effect. Finally, the three-way interaction of Display Format, Correspondence, and Control Relation was not significant, $F(1, 38) < 1$, $MSE = 682$, $\eta_p^2 = 0.003$.

For PE, the main effects of Compatibility, $F(1, 38) = 39.12$, $MSE = 17.09$, $p < 0.001$, $\eta_p^2 = 0.507$, and Control

Relation, $F(1, 38) = 15.21$, $MSE = 16.68$, $p < 0.001$, $\eta_p^2 = 286$, were significant. The interaction between these two factors was not significant, $F(1, 38) = 2.01$, $MSE = 12.72$, $\eta_p^2 = 0.052$, but the interaction between Compatibility and Display Format was significant, $F(1, 38) = 10.26$, $MSE = 17.09$, $p < 0.003$, $\eta_p^2 = 0.213$. This outcome reflects the fact that the Simon effect was larger for the aircraft-move display ($M = 6.18\%$) than for the horizon-move display ($M = 2.00\%$). The main effect of Display Format was also significant, $F(1, 38) = 4.64$, $MSE = 55.80$, $p < 0.038$, $\eta_p^2 = 0.109$ ($M_s = 7.02$ and 4.47% , respectively, for the aircraft-move and horizontal-move displays).

In contrast to Experiment 1, the Simon effect occurred based on the aircraft and hand movements, but not on the display movement. This is due to the fact that participants attended on the visual information better than those in Experiment 1 and, thus, ‘correctly’ interpreted the meaning of the display motion in terms of the aircraft movement, which is consistent with our prior studies (Yamaguchi & Proctor, 2006, 2010). Consequently, the display movement was now seen as identical with the aircraft movement, excluding the inconsistency between the display and aircraft movements.

Also, note that, comparing Experiments 1 and 2, reduction of the Simon effect in the reverse-control condition was somewhat smaller for visual stimuli (Experiment 2) than for auditory stimuli (Experiment 1). In the normal-control conditions, the Simon effect was on average 41 ms for Experiment 1 and 38 ms for Experiment 2 [$t(78) = 0.54$, $SE = 5.94$, $p > 0.2$ (one-tail)]. In the reverse-control conditions, however, the Simon effect was 2 ms for Experiment 1 and 19 ms for Experiment 2 [$t(78) = 1.83$, $SE = 9.21$, $p < 0.036$ (one-tail)].¹ Consequently, the influence of the aircraft-hand compatibility appears to be smaller for Experiment 2 than for Experiment 1. Because the stimulus modality changed from Experiment 1 to Experiment 2, the difference might have reflected a modality-specific influence on the Simon effect. However, given that the Simon effects for the normal-control conditions were equivalent between the two experiments, the difference that emerged in the reverse-control conditions is not likely due to such an influence. Instead, this outcome is most likely due to the fact that attention was focused more on the display information (aircraft movement) in the present experiment, reducing influences of other response components. Thus, the results suggest that

the Simon effect can be attentionally modulated, contradicting the automaticity assumption.

In turn, the effect of R–E compatibility between the aircraft and hand movements increased in Experiment 2 (42 ms) as compared with that of Experiment 1 (23 ms). Again, these observations seem contradictory. In Experiment 1, the influence of display movement was absent in the R–E compatibility effect but present in the SRC effect. However, in the present experiment, the influence of the hand movement increased in the R–E compatibility effect but decreased in the SRC effect, as compared with Experiment 1. Thus, there is dissociation between factors influencing the R–E compatibility effect and the SRC effect, again implying independent mechanisms for S–R and R–E compatibility.

Experiment 3

Another methodological difference between Hommel’s (1993) and Kunde et al.’s (2007) experiments was the type of responses they required in the task. In the former, responses were discrete keypresses, whereas in the latter, they were continuous control of the lever tip to a specific location. Attention toward the task-relevant response component may be facilitated in Kunde et al.’s study because the continuous monitoring of the component was required. Thus, to further enhance the influence of the task-relevant response feature (aircraft movement) and reduce that of task-irrelevant response features (display and hand movements) on the Simon effect, finer control of the aircraft was required of participants in the present experiment, so that more attention to the aircraft movement was necessary. In contrast to the preceding experiments, in which participants were only instructed to turn the aircraft to the left or right, those in the present experiment were instructed to turn the aircraft and maintain a specific attitude for a time period. Accordingly, participants were now required to monitor the attitude of the aircraft more thoroughly, increasing attentional demands on that component. If this task requirement led to further reduction, or even elimination, of the influence of irrelevant response component on the Simon effect, it provides further evidence that attention plays a key role in producing the Simon effect, in contrast to the assumption of automaticity.

Method

Participants

A new group of forty undergraduate students participated in the present experiment. They were recruited from the same subject pool as in the preceding experiments, and

¹ Because the overall mean RTs for Experiments 1 and 2 differed, we also used log-transformed RTs to perform the same analysis, which resulted in statistically the same results: $t(78) = 0.171$, $MD = 0.00178$, $SE = 0.0105$, $p > 0.4$, for the normal-control condition, and $t(78) = 1.72$, $MD = 0.0262$, $SE = 0.0152$, $p < 0.045$, for the reverse-control condition (both tests were one-tailed).

none had participated in these experiments. The mean and standard deviation of participants' ages were 19.21 and 1.47 for the aircraft-move condition and 18.75 and 1.37 for the horizon-move condition. There were 10 females in the aircraft-move condition and 12 females in the horizon-move condition.

Apparatus, stimuli, and procedure

The apparatus and stimuli were the same as those used in Experiment 2. In contrast to Experiment 2, however, the task was to move the aircraft 45° to the left or right according to the color of a visual stimulus *and* keep that position (at either of the two triangles in the bank markings) for 1 s. As the aircraft symbol points to the target triangle, the color of the triangle changed to dark blue. The aircraft was considered to be 'on target' if it was within $\pm 3^\circ$ from the target. After 1 s elapsed, a brief 'ding' sound was presented if it was the correct side, or an error tone (same as the one used in Experiment 2) was presented if it was an incorrect side, binaurally through headphones. The aircraft symbol returned to the center after a 500-ms pause screen. Experiment 3 was identical with Experiment 2 in other respects.

Results and discussion

The percentage of trials that fell outside the cut-off criteria was 0.78%. Mean RT and PE are summarized in Table 2.

For RT, there were main effects of Compatibility, $F(1, 38) = 118.06$, $MSE = 781$, $p < 0.001$, $\eta_p^2 = 0.757$, and Control Relation, $F(1, 38) = 33.29$, $MSE = 6,594$, $p < 0.001$, $\eta_p^2 = 0.467$. Responses were faster for the compatible trials ($M = 568$ ms) than for the incompatible trials ($M = 616$ ms), and for the normal-control condition ($M = 555$ ms) than for the reverse-control condition ($M = 629$ ms). In contrast to the preceding two experiments, the interaction between these factors was not significant, $F(1, 38) < 1$, $MSE = 511$, $\eta_p^2 = 0.009$. The Simon effect was comparable for the normal- and reverse-control conditions (50 and 46 ms, respectively). The interaction between Compatibility and Display Format was also not significant, $F(1, 38) < 1$, $MSE = 781$, $\eta_p^2 = 0.014$, indicating that the Simon effect was also comparable between the two display conditions (45 ms for the aircraft-move display, 51 ms for the horizon-move display). On the other hand, there was a marginal effect of Display Format, $F(1, 38) = 4.02$, $MSE = 26,574$, $p < 0.052$, $\eta_p^2 = 0.096$. This suggests that responses tended to be faster for the horizon-move display ($M = 566$ ms) than for the aircraft-move display ($M = 617$ ms).

For PE, the main effects of Compatibility, $F(1, 38) = 34.59$, $MSE = 17.24$, $p < 0.001$, $\eta_p^2 = 0.476$, and Control Relation, $F(1, 38) = 30.26$, $MSE = 30.52$,

$p < 0.001$, $\eta_p^2 = 0.443$, were significant. Responses were more accurate for the compatible trials ($M = 5.03\%$) than for the incompatible trials ($M = 8.89\%$), and for the normal-control condition ($M = 4.56\%$) than for the reverse-control condition ($M = 9.36\%$). There was no other significant effect.

The results of the present experiment are clear. The Simon effect was determined by the correspondence between the stimulus location and the aircraft movement, replicating the results of Kunde et al.'s (2007) study. Together with the results of Experiments 1 and 2, we conclude that the discrepancy between the results of Hommel's (1993) and Kunde et al.'s (2007) studies is due to the fact that attention was confined to the task-relevant response component in the latter experimental condition as compared with the former. Note, as in the present study, Kunde et al.'s participants were required to move the lever-tip to a specific position on the screen, whereas Hommel's participants were only asked to press a response key (or flash a light by pressing it). Consequently, attentional demand on the task-relevant response feature was probably high in Kunde et al.'s task. These observations suggest that influences of response components on the Simon effect are subject to attentional control.

On the other hand, whereas the influence of hand movement on the Simon effect was virtually eliminated, the aircraft-hand compatibility effect was still significant in the present experiment. In fact, the effect was larger than those observed in the preceding experiments, again suggesting dissociation between the R–E compatibility effect and the SRC effect. Implications of these findings for the underlying cognitive processes are discussed in "[General discussion](#)".

General discussion

For all experiments, the Simon effect was observed with respect to the compatibility between the stimulus location and the movement direction of the simulated aircraft, which was the task-relevant response component based on which participants were instructed on their task. In addition, in Experiment 1, the Simon effect was modulated by the two factors; display format and control relationship. Namely, the Simon effect was larger for the aircraft-move display than for the horizon-move display and for the normal-control condition than for the reverse-control condition. These results imply that the Simon effect was produced simultaneously based on multiple response components, suggesting that responses can be represented based on multiple frames of reference, much as stimuli can be represented based on multiple codes (e.g., Lamberts et al., 1992).

At the same time, in Experiment 2, the interaction between Compatibility and Display Format was eliminated. This is presumably due to the fact that, with the need of responding to visual stimuli, attention was focused more on display information so that participants were able to interpret the information correctly in terms of the aircraft movement rather than the physical movement of the display symbols, as in the task condition where pilots are able to continuously monitor the attitude display (Yamaguchi & Proctor, 2010). In addition, the interaction between Compatibility and Control Relation was also eliminated in Experiment 3, indicating that incompatibility between the stimulus location and the hand movement had little influence on the Simon effect. The outcome is attributable to the task requirement that the aircraft's roll had to be set at a specific angle, which forced the participants to focus on the aircraft movement, making it easier to ignore the hand movement. Therefore, the results of the present experiments suggest that influences of response components depend on attentional demands of the task.

Another robust phenomenon observed in the present experiments is that responses were generally faster for the normal-control condition than for the reverse-control condition. This observation corresponds to the hand-tool correspondence (or R–E compatibility) effect reported by Kunde et al. (2007). In Experiments 1 and 2, R–E compatibility affected the Simon effect, which is consistent with the results of Hommel's (1993) study. The observation implies that R–E compatibility affects the cognitive processes that are responsible for the SRC effect. Interestingly, however, although R–E compatibility did not affect the Simon effect in Experiment 3, the main effect of R–E compatibility (i.e., Control Relation) remained highly significant, suggesting that there is also a locus of the R–E compatibility effect that is independent of the mechanism responsible for the SRC effect. In other words, there are two loci of R–E compatibility.

The first cognitive mechanism affected by both S–R and R–E compatibilities is presumably responsible for translating a stimulus code into an appropriate response code (i.e., S–R translation). Suppose that, as depicted in Fig. 3 (also see Yamaguchi & Proctor, 2009), each response is composed of multiple feature codes (aircraft, display, and hand), but the response is 'represented' by the task-relevant feature (aircraft). That is, the activation of a response is equivalent to the activation of the task-relevant response feature, and whenever the task-relevant feature code is sufficiently activated, the response programming (action code; A1) can start. Stimuli can activate the task-relevant response feature code (R_r) directly by ways of direct associations between them, and indirectly by ways of activating associated task-irrelevant response feature codes

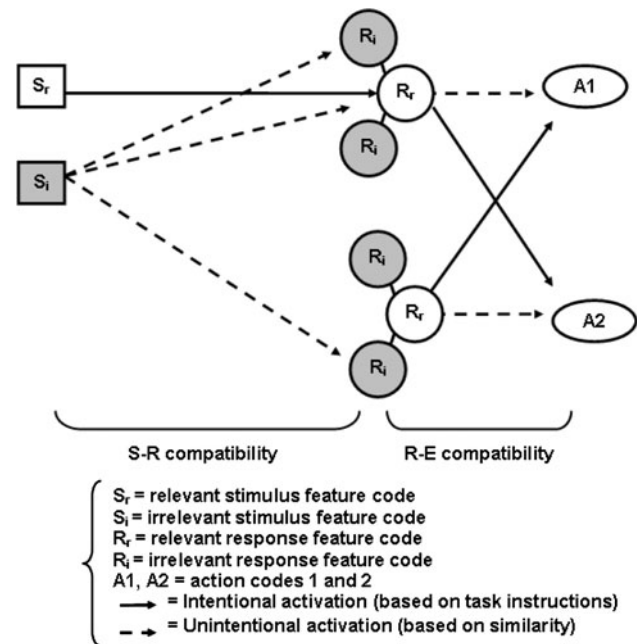


Fig. 3 Cognitive loci of the stimulus–response (S–R) and response–effect (R–E) compatibility effects

(R_i) according to the similarity between the stimuli and those response features, which then propagates to the task-relevant response feature that is associated with them. This indirect activation of the task-relevant feature code is the source of the Simon effect based on multiple response components.

At this processing stage, R–E compatibility affects the Simon effect because it determines the number of response dimensions that are compatible or incompatible with given stimuli; in other words, R–E compatibility affects the consistency of S–R compatibility relations. The results of the present study indicate that influences of these elementary response components can be weighted according to the task context. For instance, because the task of Experiment 3 required finer aircraft control, attention had to focus on the aircraft movement. Hence, the code that represents the aircraft movement is strongly weighted in that experiment, as compared with Experiments 1 and 2, eliminating the influences of other components on the activation of task-relevant feature code.

On the other hand, given that the R–E compatibility effect can occur without influencing the Simon effect, the second process should be located outside the S–R translation process. This process may be responsible for translating the activated response code into a motor command, or action code, that may correspond to the physical action required to actualize the activated response. Because the response code is represented in terms of the task-relevant component, the translation process from that response code to an action code (say, action programming) is required

when the movement directions of the task-relevant component and the physical action are different. The R–E compatibility effect emerges in that process.

The task-relevant response feature code (R_r) activates the action code (A2) with which the response code is associated through task instructions as well as the action code (A1) to which the response code is similar. In the present experiment, the task-relevant feature code is the direction of aircraft movement, and the action code is the physical hand movement. Thus, if the ‘left’ aircraft code is activated, it activates the ‘left’ hand movement even in the reverse-control condition in which the correct hand movement is ‘right.’ Consequently, responses are delayed when the aircraft and hand movements are incompatible as compared to when they are compatible, resulting in the R–E compatibility effect.

It should be stressed that the assumption that responses are represented by the task-relevant component is important in explaining the lack of the R–E compatibility effect between the display and hand movements. That is, because the action code is activated by the task-relevant component alone, the activation of task-irrelevant response feature codes cannot influence the activation of the action code. Consequently, no R–E compatibility effect between the display and hand movements occurs, as shown in the three experiments. On the contrary, if task-irrelevant response features had a direct access to the action codes, there should have been the R–E compatibility effect based on the compatibility between the display and hands, which contradict the present results.

Finally, it should also be noted that the results of Experiment 3 suggested a marginally significant effect of display format, which reflects the fact that responses were faster for the horizon-move display than for the aircraft-move display by 51 ms. This outcome may reflect the fact that a perceptual or encoding advantage emerged for the horizon-move display of Experiment 3, when more focus was directed to the display information. However, some caution is needed to interpret this effect. First, in contrast to the effect of control relation, the effect of display format was not robust in that a marginal trend was obtained only in Experiment 3. Also, the effect was not stable across experiments; RT for the horizon-move display was only 9 ms shorter than that for the aircraft-move display in Experiment 1, but it was 20 ms longer in Experiment 2. These inconsistent outcomes seem to imply that the marginal effect of display format in Experiment 3 is most likely due to sampling error, given that the factor was a between-subject variable. Because of the marginal nature of the effect, however, we remain neutral in this respect. In any case, the outcome does not affect the main conclusions of the present study.

Concluding remarks

The results of the present experiments provided three observations that are theoretically important. First, multiple response components can simultaneously produce the Simon effect. This finding parallels the previous findings that the Simon effect arises based on multiple stimulus feature dimensions (e.g., Lamberts et al., 1992). The simultaneous influences of multiple response components have not consistently been observed in previous studies (e.g., Hommel, 1993; Kunde et al., 2007; Wallace, 1971), and the present study suggests that the inconsistency is due to the fact that influences of response components depend on attentional demands imposed by the task. This flexibility of the response representation is consistent with previous studies (Guiard, 1983; Hommel, 1993) but contradicts the type of explanations of the Simon effect that assumes automatic response activation, which should be free from attentional and contextual influences. Moreover, in the present study, two effects of R–E compatibility were dissociated. First, there was general slowing of responding due to R–E incompatibility across the three experiments. The locus of this effect is shown to be independent of the cognitive process responsible for the SRC effect (i.e., S–R translation). Second, R–E compatibility can also affect the Simon effect, suggesting that it influences the S–R translation processes when the task context allows a sufficient amount of attention to be allocated to these response components.

Based on these results, we proposed a model of cognitive processes involved in the present task, for which two loci of R–E compatibility are located in the S–R translation and the action programming. It is noteworthy that Paelecke and Kunde (2007) also proposed two loci of action-effect coding. They distinguished endogenous and exogenous influences of action-effect coding. The endogenous action-effect coding is similar to the action effects used in the present study (i.e., aircraft movements), which the actor anticipates and intends to produce. The exogenous action-effect coding refers to the case in which action-effects prime actions when the effects are presented as stimuli after the contingencies between the actions and the effects have been learned. Using the psychological refractory period paradigm, Paelecke and Kunde found that the exogenous action-effect coding produced a subadditive interaction with stimulus-onset asynchrony (SOA), implying that it affected processes before the response-selection bottleneck (cf. Lien & Proctor, 2002). More important, the endogenous action-effect coding was additive with SOA, implying that the action-effect coding affected processes in (or after) the response-selection bottleneck. Therefore, Paelecke and Kunde’s results are consistent with our model, and the present study further elaborates that two

loci of the endogenous action-effect coding exist. It would be interesting to see whether the two mechanisms proposed in the present study correspond to the same processes implied by Paelecke and Kunde's study.

Acknowledgments This research was supported in part by Army Research Office grant W911NF-05-1-0153 and the Bilslund Dissertation Fellowship from Purdue University. The research was included in the first author's Ph.D. dissertation. A portion of the data reported in the present article was presented at the 15th International Symposium of Aviation Psychology, Dayton, OH. We thank Wilfried Kunde and an anonymous reviewer for constructive comments on an earlier draft.

References

- De Jong, R., Liang, C.-C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 731–750.
- Guiard, Y. (1983). The lateral coding of rotations: A study of the Simon effect with wheel-rotation responses. *Journal of Motor Behavior*, *15*, 331–342.
- Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research*, *55*, 270–279.
- Hommel, B. (2010). The Simon effect as tool and heuristic. *Acta Psychologica*. doi:10.1016/j.actpsy.2010.04.011
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review*, *97*, 253–270.
- Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 387–394.
- Kunde, W., Müsseler, J., & Heuer, H. (2007). Spatial compatibility effects with tool use. *Human Factors*, *49*, 661–670.
- Lamberts, K., Tavernier, G., & d'Ydewalle, G. (1992). Effects of multiple reference points in spatial stimulus-response compatibility. *Acta Psychologica*, *79*, 115–130.
- Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review*, *9*, 212–238.
- Lleras, A., Moore, C. M., & Mordkoff, J. T. (2004). Looking for the source of the Simon effect: Evidence of multiple codes. *American Journal of Psychology*, *117*, 531–542.
- Lu, C.-H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*, 174–207.
- Paelecke, M., & Kunde, W. (2007). Action-effect codes in and before the central bottleneck: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 627–644.
- Proctor, R. W., & Vu, K.-P. L. (2006). *Stimulus-response compatibility principles: Data, theory and application*. Boca Raton: CRC Press.
- Roswarski, T. E., & Proctor, R. W. (1996). Multiple spatial codes and temporal overlap in choice-reaction tasks. *Psychological Research*, *59*, 196–211.
- Simon, J. R. (1990). The effects of an irrelevant directional cue on human information processing. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus-response compatibility: An integrated perspective* (pp. 31–86). Amsterdam: North-Holland.
- Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology*, *86*, 97–102.
- Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*, 300–304.
- Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, *88*, 354–360.
- Wallace, R. J. (1972). Spatial S-R compatibility effects involving kinesthetic cues. *Journal of Experimental Psychology*, *93*, 163–168.
- Wang, D.-Y. D., Proctor, R. W., & Pick, D. F. (2007). Coding controlled and triggered cursor movements as action effects: Influences on the auditory Simon effect for wheel-rotation responses. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 657–669.
- Yamaguchi, M., & Proctor, R. W. (2006). Stimulus-response compatibility with pure and mixed mappings in a flight task environment. *Journal of Experimental Psychology: Applied*, *12*, 207–222.
- Yamaguchi, M., & Proctor, R. W. (2009). Transfer of learning in choice-reactions: Contributions of specific and general components of manual responses. *Acta Psychologica*, *130*, 1–10.
- Yamaguchi, M., & Proctor, R. W. (2010). Compatibility of motion information in two attitude displays for tracking task. *American Journal of Psychology*, *123*, 81–92.