Stimulus–response compatibility with wheel-rotation responses: Will an incompatible response coding be used when a compatible coding is possible?

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Three experiments were conducted in which subjects responded to left–right tones with clockwise–counterclockwise rotations of a steering wheel using one of two stimulus–response assignments. When the hands were at the bottom of the wheel, where hand movement is opposite to wheel movement, subjects coded responses according to the frame that yielded a compatible mapping when the instructions did not emphasize either hand or wheel movements (Experiment 1). When instructions emphasized hand movements, responses were coded relative to the hand-referenced frame (Experiment 2), and when the wheel controlled a visual cursor, responses were coded relative to a cursor-referenced frame (Experiment 3). Coding with respect to these frames occurred even when the resulting mapping was incompatible.

In two-choice tasks, reaction time (RT) is faster when stimulus and response are compatible, a left or right response (respectively) to a left or right stimulus, than for the opposite spatial relation, regardless of whether stimulus location is relevant or irrelevant to the task (Hommel & Prinz, 1997). This phenomenon is called the spatial stimulus–response compatibility (SRC) effect when stimulus location is relevant and the Simon effect when stimulus location is not. For both spatial SRC and Simon effects, the stimuli vary in location along the same dimension as the responses, and the effects are attributed to spatial coding of the stimuli and responses. A stimulus is assumed to directly activate the spatially corresponding response, producing facilitation when this response is correct and interference when it is not (Hommel & Prinz, 1997). Activation of the corresponding response is presumed to be the sole cause of the Simon effect, because the task does not require stimulus location to be translated into a response code. For spatial SRC proper, the compatible mapping benefits as well from faster intentional translation of the stimulus into the assigned response.

Of interest is whether SRC and Simon effects occur for situations in which the physical response bears little similarity to the stimulus dimension, such as for clockwise and counterclockwise steering-wheel rotations. Al-

though wheel rotations are not explicitly left–right, several of their features could provide a basis for left–right coding, producing SRC and Simon effects: Clockwise rotations are associated with right turns and counterclockwise rotations with left turns; the top of the wheel (which is near the line of sight) moves right for clockwise rotation and left for counterclockwise rotation; when the wheel is grasped at the top or bottom, responses may be coded with respect to the direction of hand movement. The situation in which the wheel is held at the bottom is of particular interest, because the direction of hand movement is opposite that of the wheel.

Guiard (1983) and Wang, Proctor, and Pick (2003) had subjects hold a steering wheel with both hands and respond to high- or low-pitch tones, presented in the left or right ear, with clockwise or counterclockwise wheel rotations. With neutral instructions, a Simon effect was obtained with the hands at the top or sides: RT was shorter when tone location corresponded with the typical wheel rotation (right tone with clockwise rotation; left tone with counterclockwise rotation) than when it did not. With the hands at the bottom, no overall Simon effect was evident: Some subjects showed a positive Simon effect indicative of wheel-referenced coding of responses, others a negative effect indicative of hand-referenced coding.

A question that arises is whether the individual differences in using hand- or wheel-referenced coding reflect strategies that can be altered by instructions or are fundamental biases to code responses in terms of the device

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or the anatomy. Hommel (1993) showed that the Simon effect for keypresses could be altered by instructions. Subjects responded to a high- or low-pitch tone with a left or right keypress that turned on a contralateral light. A typical Simon effect was obtained when the instructions specified which keys to press to which tones, but a reversed effect was obtained when instructions specified which lights to turn on in response to the tones. Hommel interpreted these results as support for an intended action goal hypothesis: Responses are coded in terms of the action goals, and the correspondence of stimulus location with the action goal determines the direction of the Simon effect. This intended action goal hypothesis implies that, when one is making wheel-rotation responses with the hands at the bottom, instructing subjects in terms of unambiguous action goals—that is, left–right movement of the hands or the wheel—should cause responses to be coded relative to the instructed goals.

Wang et al.'s (2003) Experiment 2 showed that instructions did influence performance, but the effects were asymmetric: Instructions emphasizing hand-movement direction yielded a negative Simon effect for all subjects, indicating that they used hand coding. However, instructions emphasizing wheel-rotation direction, or left–right movement of a red tape at the top of the wheel, produced no overall Simon effect, with the proportion of subjects showing evidence of hand-referenced and wheel-referenced coding being similar to that shown with the neutral instructions.

Although instructions that emphasized wheel movement did not cause subjects who preferred hand-referenced coding to abandon it, a visual event controlled by the wheel did. Both Guiard (1983) and Wang et al. (2003) found that when the counterclockwise–clockwise rotations of the wheel produced left–right movements of a visual cursor, all subjects showed a positive Simon effect indicative of coding relative to cursor-movement direction. This effect was absent when the cursor movement was triggered at the completion of the response (8° wheel rotation; Wang et al., 2003), suggesting that the visual-cursor movements must be tightly coupled to the controlling actions.

When performing a Simon task with the wheel held at the bottom, whether responses are coded relative to hand or wheel movement (or a cursor controlled by the wheel) influences the direction of the Simon effect but not the overall level of performance. That is, although the coding determines which combinations of stimuli and responses correspond and which do not, it does not alter the relative frequency of corresponding and noncorresponding trials. In contrast, for an SRC-proper task, overall performance depends on which reference frame is used for response coding, because only one pairing of stimulus locations to rotation directions is used in a trial block or for a given subject. With the wheel held at the bottom, a stimulus–response (S–R) mapping that is incompatible for a wheel-referenced frame will be compatible for the hand-referenced frame, and vice versa. Thus, performance will be best if responses are coded so as to always render the S–R mapping compatible, re-

gardless of whether the instructions are with respect to that reference frame or not.

Stins and Michaels (1997) examined the SRC effect for wheel-rotation responses: Subjects rotated a wheel clockwise or counterclockwise, with one hand at the top or bottom, in response to a left or right visual stimulus. Each subject performed eight trial blocks, one for each combination of hand (left or right), hand position (top or bottom), and mapping (steering consistent or inconsistent). With the hand at the top, a 46-msec SRC effect favoring the steering-consistent mapping was obtained. However, with the hand at the bottom, the overall SRC effect was -13 msec: Nine subjects showed negative SRC effects averaging -50 msec, 4 showed positive effects averaging 64 msec, and 3 showed no effect. Stins and Michaels concluded that, with the bottom placement, some subjects used hand-referenced coding and others used wheel-referenced coding.

Although Stins and Michaels's (1997) results suggest that subjects do not adopt a response coding that is optimal for the mapping, this conclusion is limited by the fact that they manipulated mapping within subjects. If subjects tend to persist in coding responses the same way across trial blocks, they may have used the most appropriate coding for the initial block and then maintained that coding for subsequent blocks. This limitation can be avoided using a between-subjects design, as we did in the present Experiment 1. Another limitation of their experiment is that it did not include instructional or display manipulations similar to those in the studies of the Simon effect, leaving open the question of whether subjects will adopt an instructed response coding, or a coding relative to a visual cursor, when such coding does not yield a compatible S–R mapping. Experiments 2 and 3 were devised to answer this question.

EXPERIMENT 1

Experiment 1 was designed to replicate Stins and Michaels's (1997) experiment using a method similar to that of Guiard's (1983) and Wang et al.'s (2003) studies. Clockwise and counterclockwise responses were made to left and right tones using one of two mappings, with both hands grasping the wheel at top, middle, or bottom positions.

Method

The experiment was conducted using a microcomputer programmed with Micro Experimental Laboratory. The apparatus is shown in Figure 1, and the stimuli are described in the caption.

Ninety-six undergraduates participated to satisfy an introductory psychology course requirement. Each subject used one mapping and one hand position, and the instructions did not verbally label the responses. Instead, the correct action was demonstrated, with the experimenter stating that the wheel should be turned "toward" or "away" from the tone. Subjects performed 10 practice trials, followed by 128 test trials at a rate of 1 trial every 5 sec. Each trial began with onset of the visual warning signal for 1 sec, followed by a tone at the signal's offset. Each stimulus occurred equally often in a pseudorandom order.

Figure 1. A person seated at the apparatus used in Experiment 1. A 14-in. VGA monitor was placed on a table, approximately 70 cm in front of the subject. A steering wheel (38-cm diameter) with the top tilted 15° away was attached to the front of the table. The wheel could turn 8° in either direction before reaching a stop and closing a switch connected to a Micro Experimental Laboratory 200A serial response box. A 1.5-cm-diameter white disk was presented in the upper part of the screen centered along the horizontal dimension as a warning stimulus. The imperative stimulus was a 2500-Hz tone of approximately 80 dB, presented monaurally to the left or right ear for 100 msec through stereo headphones. For incorrect responses, the word "error" was displayed on the screen.

Results

Five subjects were excluded for not recording a response on ≥ 20 trials or for an error rate exceeding 5%, as was a subject whose mean RT exceeded 800 msec. Trials with RT < 100 msec or > 1,000 msec were omitted. A 3 (hand positions) $\times$ 2 (mappings) $\times$ 2 (rotation

directions) analysis of variance (ANOVA) was performed for RT and percentage error (PE), with $p < .05$ for all significant effects (see Figure 2).

RT was shorter for clockwise than for counterclockwise responses (467 vs. 472 msec) [$F(1,90) = 5.44$] and for toward (439 msec) than for away (500 msec) mapping [$F(1,90) = 22.52$]. Mapping interacted with hand position [$F(1,90) = 7.93$]: The SRC effect was largest at the top (123 msec; $p < .001$), intermediate at the middle (63 msec; $p < .01$), and absent at the bottom (3 msec; $F < 1.0$).

PE was less for toward than for away mapping (0.49% vs. 0.94%) [$F(1,90) = 8.01$]. Mapping interacted with hand position [$F(1,90) = 7.99$]: The SRC effect was significant at the middle position (1.19%) [$F(1,30) = 23.36$] and almost so at the top (0.50%) [$F(1,30) = 3.44$, $p = .07$], with the difference in magnitude being nearly significant [$F(1,60) = 3.78$, $p = .057$]. For the bottom position, there was no mapping effect (-0.34%) [$F(1,30) = 1.30$].

Discussion

When the hands were at the top and middle positions, RT was shorter and PE lower for turning the wheel toward the tones than away from them. However, this SRC effect was not evident when the hands were at the bottom of the wheel. The absence of an SRC effect for responses at the bottom position could be explained in two ways: First, as in the Simon task, subjects may select different action goals, turning the wheel or moving the hands, which are in opposition and cancel out when averaged across subjects (Wang et al., 2003). Second, subjects may use the response coding that is compatible with the stimulus locations (wheel-referenced coding for the toward mapping and hand-referenced coding for the away mapping).

Our results provide evidence consistent with the second account: Performance with the away mapping was better when the hands were at the bottom of the wheel than when they were at the other positions. Also, if some subjects used wheel-referenced coding and others hand-

Figure 2. Mean reaction time (RT) in milliseconds and mean percentage error for Experiment 1 as a function of hand position and S-R mapping. Error bars show the standard error.

referenced coding, within each mapping the between-subjects standard deviation should be larger for the bottom position than for the top and middle positions. However, the standard deviations within each combination of mapping and hand placement were not largest with the bottom hand placement for either the toward ($SDs = 47, 62$, and 47 msec for the top, middle, and bottom placements, respectively) or away mapping ($SDs = 78, 69$, and 70 msec, respectively). Our results agree with those of Merz, Kalveram, and Huber (1981) for control of a left–right cursor in a tracking task with lateral knob pressure. They found that subjects could code an incompatible mapping of cursor movement to knob pressure in terms of a compatible relation of cursor movement to wheel-rotation direction when the knob was placed at the bottom of a visible steering wheel.

Our conclusion that at the bottom hand position, subjects coded responses in a way that maintained compatibility for both mappings is different from the conclusion of Stins and Michaels (1997) that some of their subjects used wheel-referenced and others hand-referenced coding for both mappings. This difference is likely due to the use of between-subjects versus within-subjects manipulations. When subjects experience both mappings, as in Stins and Michaels's study, they may continue using the initial coding even when it results in an incompatible mapping.

The SRC effect for RT was larger for the top than for the middle hand position. However, the PE data showed the opposite interaction, with the SRC effect smaller for the top than for the middle position. Due to this speed–accuracy tradeoff, the RT data cannot be interpreted unambiguously as showing a combined contribution of hand- and wheel-referenced coding. Because our previous study showed no evidence of a larger Simon effect for the top position than for the middle position, it is safest to conclude tentatively that the additional correspondence of hand movement with wheel movement at the top position does not increase the magnitude of the SRC effect.

EXPERIMENT 2

In Experiment 2, all subjects used the bottom hand placement, with instructions in terms of left–right movement of the hands or of red tape placed at the top of the wheel. If subjects adopt the instructed action goals, SRC effects should be obtained for which the direction is determined by those goals. However, if subjects do not adopt the instructed action goals when they yield an incompatible S–R mapping, but always code the responses relative to the frame that yields a compatible mapping, then there should be no SRC effect.

Method

Sixty-four new undergraduates participated. The stimuli and apparatus were the same as in Experiment 1. Half the subjects received the toward mapping and half the away mapping. Hand instructions described the responses as moving the hands left or right; red-tape instructions described the responses as moving a 1.5-cm-wide red tape at the top of the wheel left or right.

Results

Eleven subjects did not meet the aforementioned criteria and were replaced.

Clockwise responses were faster than counterclockwise responses (498 vs. 505 msec) [$F(1,60) = 4.75$]. The main effect of mapping was significant [$F(1,60) = 7.51$], as was the interaction with instructions [$F(1,60) = 5.95$] (see Figure 3). For the red-tape group, there was no mapping effect (516 msec for toward, 511 msec for away) ($F < 1.0$), but for the hand-instruction group, RT was shorter when responses were compatible with the direction of hand movement (away mapping, 440 msec) than when they were not (toward mapping, 540 msec) [$F(1,30) = 16.86$].

PE was higher for toward (1.11%) than for away (0.60%) mapping [$F(1,60) = 5.47$], and this effect did not interact with instructions [$F(1,60) = 1.12$]. Also, rotation direction and its interaction with instructions were significant [$F_s(1,60) = 4.93$ and 12.19 , respectively]. Clockwise ro-

Figure 3. Mean reaction time (RT) in milliseconds and mean percentage error for Experiment 2 as a function of instructions (hand vs. red-tape) and S–R mapping. Error bars show the standard error.

tation had fewer errors overall than did counterclockwise rotation (0.65% vs. 1.06%), with this difference significant only for the hand-instruction group (0.36% vs. 1.41%) [$F(1,30) = 17.67$].

Discussion

The hand-instruction group showed a negative SRC effect relative to wheel-rotation direction. This result implies that subjects used hand-referenced coding when instructed in terms of hand movement, even when this coding resulted in an incompatible S–R mapping. In contrast, the red-tape instruction group showed no SRC effect: Performance was worse for both mappings (RTs of 516 and 511 msec, respectively, for toward and away and PEs of 0.96% and 0.68%, respectively) than was that for the away mapping with hand instructions (RT of 440 msec and PE of 0.51%). This outcome suggests that the absence of SRC effect for the red-tape instructions was not due to subjects consistently coding responses in terms of the reference frame that would yield a compatible mapping. Instead, the responses were apparently not being coded consistently in terms of the instructed wheel-referenced frame even when this coding would yield a compatible mapping.

EXPERIMENT 3

When a wheel is turned to operate a vehicle or a display element, visual stimulation changes systematically due to the causal control of the wheel on the system. In Experiment 2, however, because the red tape was affixed to the wheel, its movement was a passive consequence of the wheel rotation. Also, the tape may not have been clearly perceived as moving left or right, because its motion covered only a small distance (4.3 cm) and was not solely along the horizontal axis. The failure of the red-tape instructions to induce a consistent action goal for all subjects could have resulted from either of these properties.

In Experiment 3, the visual event was motion of a cursor that moved along the horizontal axis of the screen. In one condition, left–right cursor motion was controlled directly by the wheel; in the other, it was triggered at completion of the 8° wheel rotation. If clear left–right motion of the cursor provides a sufficient action goal regardless of the mapping, then both conditions should show an SRC effect. However, if perception of causal control is necessary, an SRC should be evident only in the controlled-cursor condition.

Method

Sixty-four new undergraduates participated. The experiment was programmed using LabView 5.1. The apparatus, stimuli, and procedure were the same as in the previous experiments, except as noted (see Figure 4). All subjects responded with the bottom hand position, as in Experiment 2, and were instructed as in Experiment 1.

Results

Five subjects were replaced using the aforementioned criteria.

Figure 4. Schematic of the display screen for Experiment 3. A small cursor moved left or right with counterclockwise or clockwise rotation of the wheel, along a horizontal line that spanned the display screen. A vertical line bisected the screen from top to bottom. The lines' intersection marked the neutral position for the cursor, 12 cm from the left and right edges of the effective region of the display. For the triggered-cursor condition, cursor movement was triggered when the wheel rotation closed one of the response switches; the cursor then moved 8.5 cm over 200 msec in the appropriate direction. For the controlled-cursor condition, the cursor moved continuously with displacement of the wheel, returning to the neutral position when the wheel was centered to begin a trial.

RT was shorter for toward (505 msec) than for away (571 msec) mapping [$F(1,60) = 11.58$]. Mapping tended to interact with cursor type [$F(1,60) = 3.97, p = .051$] (see Figure 5). The SRC effect was significant with the controlled cursor (104 msec) [$F(1,30) = 14.01$], but not with the triggered cursor (27 msec) [$F(1,30) = 1.03$]. There was no significant difference between the controlled (499 msec) and triggered (511 msec) cursors for the toward mapping ($F < 1.0$), but a longer RT occurred with the controlled (603 msec) than with the triggered cursor (538 msec) for the away mapping [$F(1,30) = 5.51$].

PE was greater for away (2.1%) than for toward (1.1%) mapping [$F(1,60) = 7.58$]. This SRC effect was significant for the controlled cursor [$F(1,30) = 4.28$] and almost significant for the triggered cursor [$F(1,30) = 3.36, p = .077$].

Discussion

The controlled-cursor condition showed SRC effects of similar magnitude to those obtained with the hands at the top of the wheel in Experiment 1 and, in the opposite direction, for the hand-instruction group in Experiment 2. This large SRC effect suggests that the responses were coded in terms of cursor movement, regardless of whether the mapping of the movement to the tones was compatible or incompatible.

The triggered-cursor condition showed only a small, nonsignificant SRC effect. With the toward mapping, RT was only 12 msec slower than for the controlled-cursor condition, and with the away mapping, RT increased much less than for the controlled-cursor condition. The rel-

Figure 5. Mean reaction time (RT, in milliseconds) and mean percentages of error for Experiment 3 as a function of cursor movement (controlled vs. triggered) and S-R mapping. Error bars show the standard error of the mean.

atively fast reactions for both mappings in the triggered-cursor condition suggests that subjects coded the responses relative to the frame that yielded a compatible mapping—that is, wheel-referenced for the toward mapping and hand-referenced for the away mapping. The combined results for both cursor conditions are consistent with the hypothesis that perception of causal control is crucial to coding responses in terms of action goals.

GENERAL DISCUSSION

Performance of an SRC task will be best if the response coding used is one that renders the S-R mapping compatible. In Experiment 1, an SRC effect was evident for RT and PE when the wheel was held at the top or middle positions, for which the mapping of right-clockwise/left-counterclockwise is compatible for all reference frames. However, when the wheel was held at the bottom, no SRC effect was evident. For both mappings, RT was approximately as fast as that for the compatible mapping with the middle-hand position. This outcome suggests that a wheel-referenced frame was used for the right-clockwise/left-counterclockwise assignment but a hand-referenced frame for the right-counterclockwise/left-clockwise assignment.

Coding with respect to the hand-referenced frame was used in Experiment 2 when instructions specified moving the hands left or right: A negative SRC effect was obtained of similar absolute magnitude to those effects obtained with the top- and middle-hand placements in Experiment 1. This negative SRC effect indicates that, unlike those instructed to turn away or toward the tone in Experiment 1, subjects coded the responses in terms of the instructed hand movements even when this coding resulted in an incompatible S-R mapping. Instructing subjects to move the red tape at the top of the wheel to the left or right did not yield an SRC effect, and the subjects' relatively poor performance suggests that these instruc-

tions did not induce a consistent use of wheel-referenced response coding.

Experiment 3 demonstrated that response coding could be determined by a visual event caused by wheel rotation: A large positive SRC effect occurred when the wheel controlled the left-right movement of a visual cursor. As with the SRC effect obtained with hand-movement instructions in Experiment 2, this result indicates that the responses were coded relative to the same frame, in this case cursor movement, regardless of whether the resulting mapping was compatible or incompatible. Continuous control of the cursor is apparently important, as no significant SRC effect was evident when the cursor was triggered on completion of the wheel-rotation response.

The results of the present study are consistent with the main point of Hommel's (1993) intended action goal hypothesis: When alternative action goals are possible, as when a subject responds with the hands at the bottom of the wheel, the cognitive representation of the action goal determines the pattern of SRC effects. Our results highlight factors that determine which reference frame will be used for coding the intended actions. When instructions are relatively neutral, the reference frame that yields the best performance tends to be adopted. However, when given hand-movement instructions or a visual cursor controlled by the wheel, responses are coded with respect to the hand-referenced and cursor-referenced frames, respectively, even when the resulting mapping is incompatible. The tendency for all subjects to code responses relative to the hands when instructions emphasize hand movements is in agreement with our results for the Simon task and suggests that hand-referenced coding is more natural than wheel-referenced coding, possibly because it is more obviously left or right. A cursor controlled by the wheel movement provides a salient left-right spatial feature and thus enables coding with respect to this environmental frame. Unlike keypress responses (Hommel, 1993), a visual event that occurs upon completion

of the response is not sufficient to cause that event to be coded as the action goal, possibly because no causal relation between the wheel movement and the visual event is perceived.

It is of interest that the results of the present SRC study are similar to those of the Simon-effect studies (Guiard, 1983; Wang et al., 2003) even though the reference frame determines only the direction of the Simon effect but, for the SRC task, determines the overall level of performance for the particular S–R mapping that is in effect. The facts that hand-focused instructions induce hand-referenced coding and that control of a visual cursor induces cursor-referenced coding, even when the resulting S–R mapping is incompatible, imply that these variables do not merely bias a choice of which alternative coding is adopted, but directly cause subjects to use this coding even when it is detrimental to performance.

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