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Representing response position relative to display location: Influence on orthogonal stimulus–response compatibility

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Two types of stimulus–response compatibility (SRC) effect occur with orthogonal stimulus and response sets, an overall up–right/down–left advantage and mapping preferences that vary with response position. Researchers agree that the former type is due to asymmetric coding of the stimulus and response alternatives, but disagree as to whether the latter type requires a different explanation in terms of the properties of the motor system. This issue is examined in three experiments. The location of the stimulus set influenced orthogonal SRC when it varied along the same dimension as the responses (Experiments 1 and 2), with the pattern predicted by the hypothesis that the stimulus set provides a referent relative to which response position is coded. The effect of stimulus-set location on orthogonal SRC was independent of the stimulus onset asynchrony (SOA) for a marker that indicated stimulus-set side and the imperative stimulus. In contrast, a spatial correspondence effect for the irrelevant stimulus-set location and response was a decreasing function of SOA. Experiment 3 showed that the orthogonal SRC effect was determined by response position relative to the stimulus-set location and not the body midline. The results support the view that both types of orthogonal SRC effects are due to asymmetric coding of the stimuli and responses.

When the stimulus and response sets in a choice-reaction task vary along the same spatial dimension, responses are faster and more accurate when the stimuli are assigned to their corresponding responses than when they are not. In a two-choice task, performance is better with a mapping of right stimulus to right response and left stimulus to left response than with the opposite mapping (see Hommel & Prinz, 1997; Proctor & Reeve, 1990). This benefit for the corresponding mapping is called a spatial *stimulus–response compatibility* (SRC) effect. A benefit for spatial correspondence is also evident when the relevant stimulus dimension is nonspatial but the stimulus varies on an irrelevant location dimension that is the same for the responses (Lu & Proctor, 1995). This effect of irrelevant location correspondence is called the *Simon effect*, after the individual who first reported it (Simon, 1990). The SRC and Simon effects also occur when arrows or location words convey the location

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information and when the responses are spoken location names. These effects are assumed to be a consequence of the conceptual similarity between the stimulus-location and response-location dimensions.

Based on the view that SRC effects originate in conceptual similarity, no such effects would be expected when the stimuli and responses vary along orthogonal spatial dimensions (e.g., up–down stimuli mapped to left–right responses). That is, because the stimulus dimension is not conceptually similar to the response dimension, there would seem to be no basis for one stimulus–response (S–R) mapping to be better than the other. However, beginning with Bauer and Miller's (1982) study, it has been consistently found that the S–R mapping affects performance even when the dimensions along which the stimulus and response sets vary are orthogonal, a phenomenon called the *orthogonal SRC effect*.

Two types of explanation for orthogonal SRC effects have been proposed. One type attributes orthogonal SRC to asymmetric coding (positive and negative polarity) of the stimulus and response alternatives, presuming performance to be best when the polarities of the stimulus alternatives are mapped to the corresponding polarities of the response alternatives (e.g., Cho & Proctor, 2001; Umiltà, 1991; Weeks & Proctor, 1990). The other type of explanation attributes orthogonal SRC to properties of the motor system (e.g., Bauer & Miller, 1982; Lippa & Adam, 2001; Michaels, 1989), presuming that the state of the motor system determines which responses can be made most easily to the particular stimuli.

Lippa and Adam (2001) proposed that both types of explanation are appropriate, but for distinct categories of orthogonal SRC effects. The first category is an overall *up–right/down–left advantage* that is often found when up–down stimuli are mapped to left–right responses. This advantage occurs with a variety of stimulus sets, including physical up–down locations (Weeks & Proctor, 1990) and the location words "above" and "below" (Proctor, Wang, & Vu, 2002), as well as with a variety of response sets, including unimanual left–right movements, bimanual keypresses, unimanual keypresses, and the spoken words "left" and "right" (e.g., Adam, Boon, Paas, & Umiltà, 1998; Cho & Proctor, 2001). According to Lippa and Adam, the up–right/down–left advantage can be attributed to asymmetric coding of the stimulus and response alternatives.

The second category of orthogonal SRC effects identified by Lippa and Adam (2001) includes those for unimanual responses that vary as a function of the responding hand and the position of the response device. With unimanual left–right movements of the hand to a target location, or of a switch or joystick, the preferred mapping varies as a function of the position along the transverse plane at which the responses are made (e.g., Cho & Proctor, 2002; Michaels, 1989), a phenomenon called the *response eccentricity effect*: Regardless of whether the left or right hand is used, an up–right/down–left advantage occurs when responding in the right hemispace and an up–left/down–right advantage when responding in the left hemispace. According to Lippa and Adam, this second category of effects requires an explanation in terms of the state of the motor system.

Weeks and Proctor (1990) proposed the first asymmetric coding account of the overall up–right/down–left advantage: the salient features coding hypothesis. They noted that word–picture verification tasks indicate that the codes for "up" and "right" are more salient (i.e., are of positive polarity) than those for "down" and "left" (which are of negative polarity), respectively (e.g., Chase & Clark, 1971; Olson & Laxar, 1973). This difference in polarity is often attributed to the negative member being marked relative to the positive member (e.g., Just & Carpenter, 1975). Weeks and Proctor concluded that the up–right/down–left mapping benefits from the correspondence of the positive (up and right) and negative (down and left) members of the S–R sets. Umiltà (1991) and Adam et al. (1998) agreed that asymmetric coding of the type suggested by the salient features coding hypothesis is the source of the up–right/down–left advantage, but they argued that this asymmetry is restricted to verbal codes. However, the evidence provides little support for their position and suggests that asymmetric coding is a general property of categorical spatial codes and verbal codes (Cho & Proctor, 2001, 2003; Proctor & Cho, 2001).

Although Lippa and Adam (2001) conceded that the up–right/down–left advantage can be attributed to asymmetric coding, they proposed a motor-system account, called the end-state comfort hypothesis, to explain the response eccentricity effect obtained with unimanual responses. According to this hypothesis, the response dimension is cognitively transformed to map the response set onto the stimulus dimension in the same frame of reference. With a vertical stimulus set and horizontal response set, the response board or responding hand is mentally rotated clockwise or counterclockwise to align the representation with the vertical orientation of the stimulus set. The direction of the mental rotation for the hand is automatically determined by the principles and constraints of real movement. Specifically, rotation is in the direction that would result in the most comfortable end-state if the hand were actually rotated. Inward rotational movement is more comfortable than outward rotational movement when the responding hand is placed in the ipsilateral hemispace, whereas outward rotational movement is more comfortable than inward rotational movement when the responding hand is placed in the contralateral hemispace. These relations imply that, regardless of which hand is used for responding, an up–right/down–left advantage will occur when responding in the right hemispace and an up–left/down–right advantage when responding in the left hemispace, consistent with empirical results (e.g., Weeks, Proctor, & Beyak, 1995).

One shortcoming of Lippa and Adam's (2001) account of orthogonal SRC effects is that it attributes one category of effects (the overall up–right/down–left advantage) to one mechanism—correspondence of asymmetric codes—and the other category (effects of response-related variables) to another mechanism—alignment of the response dimension with that of the stimulus dimension in the direction dictated by end-state comfort. Cho and Proctor (2003) have developed an alternative explanation of the second category of effects, which we call the multiple asymmetric codes account, that extends Weeks and Proctor's (1990) salient features coding hypothesis for the up–right/down–left advantage to the response-related effects. The central idea is that the response alternatives are coded not just relative to one frame of reference but relative to several frames of reference, with the magnitude and direction of the orthogonal SRC effect depending on the summed contributions of the different codes.

As in Weeks and Proctor's (1990) salient features coding account, the stimuli and responses are assumed to be coded asymmetrically along their respective dimensions, with one member of each pair coded as positive polarity and the other as negative polarity. There is a benefit to performance when the mapping maintains correspondence of the stimulus polarities with those of any pair of response codes. When the responses are positioned neutrally (e.g., unimanual left–right movements at body midline, keypresses with the left and right keys centred around midline, and vocal "left"–"right" responses), vertically arrayed stimuli are coded with up as positive polarity and down as negative polarity, and the horizontally arrayed responses are coded with right as positive polarity and left as negative polarity. The correspondence of polarities for the up–right/down–left mapping but not for the opposite mapping yields the up–right/down–left advantage.

When response position is varied (e.g., in different trial blocks, unimanual responses are made in the left hemispace, body midline, and right hemispace), the response alternatives are also coded based on the position at which the responses are made relative to several reference frames. Because the positive and negative response codes for right and left evident at the neutral midline position contribute to performance at all response positions, an overall up–right/down–left advantage typically is found. When the response position is in the right hemispace, it is represented as being right relative to several possible referents (e.g., it is to the right of the display screen), and additional response codes are generated with respect to each referent for which the right response alternative is coded as positive and the left response alternative as negative. Because the additional response codes are positive for right and negative for left, the up–right/down–left advantage obtained at body midline increases. Likewise, when the response position is in the left hemispace, it is represented as being left with respect to several possible referents, and additional response codes are generated for which the left response alternative is coded as positive and the right response alternative as negative. Consequently, the up–right/down–left advantage tends to reverse to an up–left/down–right advantage. This reversed effect in the left hemispace typically is not as large as the positive effect in the right hemispace because the influence of the additional response location codes is superimposed on that of the response code that produces the up–right/down–left advantage in the neutral position.

The primary support for this multiple asymmetric codes explanation comes from several demonstrations that variables that provide a referent relative to which response position is coded have effects on orthogonal SRC similar to that of response eccentricity. In Weeks et al.'s (1995) Experiment 2, participants made unimanual left–right toggle-switch movements at the body midline to a vertical stimulus set. An inactive toggle switch was placed to the right of the active toggle switch in one condition and to the left in another. Although the responses were made at the same centred location in both cases, the up–right/down–left advantage obtained when the active switch was located right of the inactive switch decreased to a nonsignificant up–left/down–right advantage when the active switch was located left of the inactive switch. Proctor and Cho (2003) replicated this effect of relative location of the active response apparatus and showed that it and the response eccentricity effect also occur for keypress responses made with the left and right index fingers—results that are not predicted on the basis of end-state comfort.

Cho and Proctor (2002) provided evidence that, for unimanual responses, hand (left or right) and hand posture (prone or supine) effects on orthogonal SRC are also due primarily to coding the location of the response switch, in this case relative to the main part of the hand: The up–right/down–left advantage obtained when the switch is to the right of the main part of the hand (as, for example, when the switch is grasped between the index finger and thumb of the left hand in a prone posture) is reduced or reversed when the switch is to the left of the main part of the hand (as, for example, when the switch is grasped between the index finger and thumb of the right hand in a prone posture). Note that the general principle that emerges across these various manipulations is that the up–right/down–left advantage increases when the response position is coded as right relative to any referent object compared to when it is coded as left.

Because the end-state comfort hypothesis cannot in principle offer an explanation of the overall up–right/down–left advantage, it necessarily is restricted to the effects that vary with response position. In contrast, the multiple asymmetric codes account not only explains the overall up–right/down–left advantage, but is capable in principle of providing an explanation for the second category of orthogonal SRC effects as well. Thus, it is important to resolve the issue of whether the orthogonal SRC effects that vary with response position can also be attributed to asymmetric coding or whether they require a separate explanation in terms of end-state comfort.

Although studies of this category of orthogonal SRC effects have focused primarily on response variables, stimulus manipulations have the potential to discriminate between the asymmetric coding and end-state comfort accounts. In particular, the multiple asymmetric codes account predicts that varying the location of the stimulus set or display relative to the response position should have similar effects to those found with other referent objects. When the display is to the left, the response position is right relative to the display, which allows a response coding for which right is positive, and left is negative; in contrast, when the display is to the right, the response position is left relative to the display, which allows a response coding for which left is positive, and right is negative. Consequently, the up–right/down–left advantage should be larger when the stimulus display is to the left of the response position than when it is to the right. Also, because relative location coding of response position is not restricted to unimanual responses, the multiple asymmetric codes account predicts that the qualitative pattern of results obtained for the manipulation of stimulus-set location should also occur for other response modes. Because the end-state comfort account has been formulated only to apply to effects obtained with unimanual responses and has no mechanism to accommodate effects of stimulus-set location, it does not predict an effect of stimulus-set location nor that this effect will be similar across response modes.

Therefore, in the present study, we manipulated the location of the stimulus set relative to the response position using four response modes: unimanual left- and right-hand switch movements, bimanual keypresses, and vocal responses. In Experiment 1, participants made left–right responses to stimuli presented above or below a row of plus signs shown in the left or right half of the display screen 500 ms prior to the stimulus. All manual responses were made at a centred location, and the location of the stimulus set was varied along the same dimension as the responses (horizontal) to determine whether stimulus-set location has the effect on orthogonal SRC that is predicted by the multiple asymmetric codes account. The results of Experiment 1 showed a Simon effect for correspondence of the irrelevant stimulus-set location with response location in addition to an orthogonal SRC effect. In Experiment 2 a similar methodology was used, except that the stimulus onset asynchrony (SOA) between the fixation row that signalled stimulus-set location and the imperative stimulus was varied from 50–650 ms, with the intent of dissociating the two effects. The Simon effect typically decreases as SOA increases (Hommel, 1993), most likely due to the irrelevant activation dissipating. However, if stimulus-set location exerts its influence on orthogonal SRC by serving as a referent relative to which response position is coded, this influence should not vary across SOAs.

In Experiment 3, the effects of response position relative to the stimulus set and hand position relative to body midline were separated by varying response location in two ways: Either the participant's position remained fixed, and the display screen and responses were placed together to the left, right, or centre of the participant, or the display screen remained fixed, and the participant and responses were placed to the left, right, or centre of the display. According to the multiple asymmetric codes account, response location relative to the stimulus set should be most important, whereas according to the end-state comfort account, hand position relative to body midline should be.

EXPERIMENT 1

In Experiment 1, the stimulus set was arrayed vertically and the response set horizontally, and the location of the stimulus set was manipulated horizontally, along the dimension on which the responses varied. The imperative stimulus was presented above or below a fixation row shown on the left or right half of the screen. Left–right responses were made in one of four response modes: unimanual switch movements made with the left or right hand, bimanual keypresses, and the vocal utterances "left"–"right."

Based on prior studies, we expected to obtain an overall up–right/down–left advantage. As described in the Introduction, the multiple asymmetric codes account predicts this outcome on the basis of coding asymmetry, but the end-state comfort account does not. Evidence summarized in the Introduction also indicates that response position is represented with respect to multiple frames of reference, including an irrelevant response apparatus and, for unimanual responses, the main part of the hand. When the response position is represented as right with respect to any reference frame, the right response is coded as positive polarity and the left response as negative polarity, increasing the up–right/down–left advantage. The opposite holds when the response position is represented as left. Because the stimulus set provides a referent relative to which response position can be represented, the multiple asymmetric codes account predicts that the up–right/down–left advantage should be larger when the response position is represented as right (i.e., the stimulus set is to the left) than when it is represented as left (i.e., the stimulus set is to the right). In contrast, the end-state comfort account makes no prediction for the bimanual or vocal response modes, and it predicts no effect of stimulus-set location for the unimanual response modes because this display variable does not affect the movement constraints of the responding hand.

Method

Participants

A total of 96 undergraduate students enrolled in introductory psychology at Purdue University participated in partial fulfilment of a course requirement. All of the participants were required to be right handed and have normal or corrected-to-normal visual acuity, as indicated by self-report. Participants were randomly assigned to the four response modes.

Apparatus and stimuli

The experiment was controlled by software developed with the Micro Experimental Laboratory (MEL 2.1) system. Stimuli were presented on the display screen (14 in.) of a personal computer, viewed at a distance of approximately 60 cm. For each response mode, the appropriate response device was placed at the participant's sagittal midline. For vocal responses, the word "left" or "right" was spoken into a microphone interfaced with the computer through a MEL response box. For the bimanual keypresses, the leftmost or rightmost response button on the five-button response box was pressed with the left or right index finger. The unimanual responses were made with a unidimensional joystick, 5.5 cm high and 1.4 cm in diameter, mounted on a 16 × 16-cm surface of a box of height 11.5 cm. The joystick was grasped between the thumb and index finger of the appropriate hand, with the arm held in a comfortable position such that the wrist-to-fingertip axis was slightly off vertical, and required a movement of 1.2 cm in one direction or the other to close a switch. The joystick was pushed left or right with the left hand for the left-hand unimanual response mode and with the right hand for the right-hand unimanual response mode.

Stimuli were uppercase Xs (0.3 × 0.4 cm, approximately 0.29° × 0.39° of visual angle). They were presented as white characters on a dark background, 2 cm (1.91°) above or below a fixation row "+++" (0.9 × 0.3 cm, 0.86° × 0.29°), presented to the left or right side, with a gap of 6 cm (5.73°) between the centre of the screen and the inner side of the row.

Procedure

Each participant performed the task with both the up–right/down–left and the up–left/down–right mappings, with the order of the mappings counterbalanced across participants. Each participant performed 20 practice trials and 200 test trials for each mapping condition. The test trials were presented in two blocks of 100 (50 randomly assigned to each stimulus position), with a 1-min interval between trial blocks and a 2-min interval between mapping conditions.

Each trial began when a single asterisk flashed in the centre of the screen. Participants were asked to focus on this asterisk. After 250 ms, it disappeared, and the fixation row of plus signs was presented to the left or right of the asterisk's location. After 500 ms the stimulus "X" appeared above or below the fixation row, and both remained on until the participant responded. The asterisk for the next trial appeared 1 s after the response. An incorrect response was followed by a 500-ms feedback tone and then the 1-s intertrial interval.

Results

RTs shorter than 125 ms and longer than 1,250 ms were removed as outliers in this and the subsequent experiments. A small percentage of trials (1.11%) was removed from analysis using these criteria. Mean reaction time (RT) and percentage error (PE) were calculated for each participant as a function of mapping, stimulus-set location (left, right), and response (left, right). Analyses of variance (ANOVAs) were conducted on the mean RT and PE data, with those variables as within-subject factors and response mode as a between-subject factor (see Table 1).

Reaction time. The response mode main effect was significant, $F(3, 92) = 32.02$, $p < .0001$, $MSE = 33{,}517$. RT was shortest for bimanual keypresses ($M = 372$ ms), intermediate for vocal responses ($M = 415$ ms), and slowest for the left-hand and right-hand unimanual responses (Ms = 512 and 527 ms, respectively).

The mapping main effect was significant, $F(1, 92) = 11.96$, $p = .0008$, $MSE = 3{,}301$. RT was 14 ms faster with the up–right/down–left mapping ($M = 450$ ms) than with the up–left/down–right mapping ($M = 464$ ms). The Mapping × Response Mode interaction was not significant, $F(3, 92) = 2.08$, $p = .1082$, $MSE = 3{,}301$, and the up–right/down–left advantage was evident numerically for all response modes (11 ms with vocal responses, 10 ms with bimanual

TABLE 1
Mean reaction time[a] and percentage of error in Experiment 1 as a function of mapping, location of stimulus set, and response mode

	Stimulus-set location											
	Left						*Right*					
	Up–left/ down–right		*Up–right/ down–left*		*Mapping effect*		*Up–left/ down–right*		*Up–right/ down–left*		*Mapping effect*	
Mode	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*
Vocal	423	1.30	408	0.63	15	0.67	420	0.64	412	0.88	8	−0.24
Bimanual	381	3.84	365	1.97	16	1.87	374	3.10	370	3.19	4	−0.09
Right-hand	534	3.49	522	3.49	12	0.00	525	2.61	527	3.31	−2	−0.70
Left-hand	533	4.29	492	1.61	41	2.68	522	3.66	500	1.96	22	1.40
Mean	468	3.23	447	1.93	21	1.40	460	2.50	452	2.33	8	0.17

Note: Right-hand denotes the right-hand unimanual response mode, and left-hand denotes the left-hand unimanual response mode.

[a] In ms.

keypresses, 5 ms with right-hand unimanual responses, and 32 ms with left-hand unimanual responses). Note that the largest difference, that between the right- and left-hand unimanual responses, is expected on the basis of the position of the response switch also being coded relative to the main part of the hand (Cho & Proctor, 2002), and the "neutral" up–right/down–left advantage for unimanual responses is the average of these two conditions, 19 ms.

Only response interacted with response mode, $F(3, 92) = 5.21$, $p = .0023$, $MSE = 1{,}664$. The right response tended to be faster than the left response for the vocal, bimanual, and left-hand unimanual modes (3, 15, and 13 ms, respectively), but RT was 15 ms slower for the right response than the left response for the right-hand unimanual response mode. This difference is probably due to motoric properties of the responding limb. In both unimanual response modes, the movements toward the inside were easier and faster than the movements toward the outside. No other main effects or their interactions with response mode were significant.

Most important, the interaction between mapping and stimulus-set location was significant, $F(1, 92) = 22.45$, $p < .0001$, $MSE = 363$. When the stimulus set was presented on the left side of the screen, a 21-ms up–right/down–left advantage occurred, $F(1, 92) = 24.09$, $p < .0001$, $MSE = 1{,}733$, but when the stimulus set was presented on the right side, the up–right/down–left advantage was only 8 ms, $F(1, 92) = 3.04$, $p = .0845$, $MSE = 1{,}931$ (see Figure 1). Moreover, this effect did not interact with response mode, $F(3, 92) < 1.0$.

Another interesting finding is that the Response × Stimulus-Set Location interaction was significant, $F(1, 92) = 31.81$, $p < .0001$, $MSE = 728$. For the left stimulus-set location, the left response was 10 ms faster than the right response, but for the right location, the right response was 12 ms faster than the left response. This Simon effect for stimulus-set location did not interact with response mode, $F(3, 92) = 2.11$, $p = .1043$, $MSE = 728$. There was no

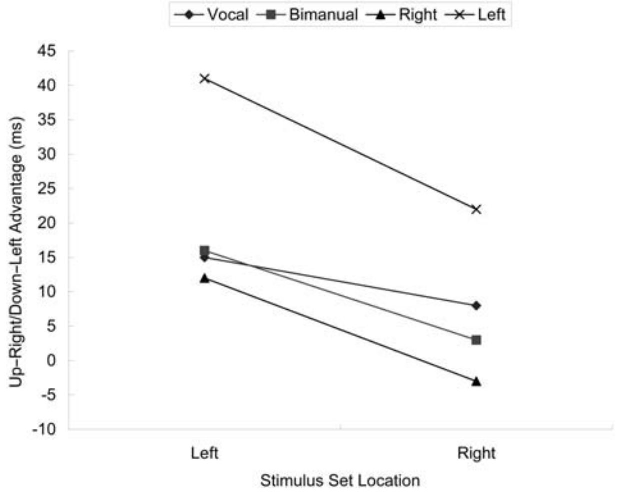

Figure 1. The up–right/down–left advantage as a function of stimulus-set location and response mode for reaction time in Experiment 1.

other significant interaction, but the interaction of mapping, response, and stimulus-set location showed a nonsignificant trend, $F(1, 92) = 3.76$, $p = .0556$, $MSE = 476$. With the right response, the magnitude of the up–right/down–left advantage was 23 ms when the stimulus set appeared on the left side of the screen and 4 ms when it appeared on the right side. With the left response, those values were 19 ms and 11 ms, respectively. That is, the effect of stimulus-set location on the mapping effect tended to be greater with the right response than with the left response.

Percentage of error. Overall PE was 2.50%. The main effect of response mode was significant, $F(3, 92) = 5.17$, $p = .0024$, $MSE = 44.91$. As usual, a post hoc Scheffe test showed that PE was lowest with vocal responses (0.86%), but PEs with bimanual and left- and right-unimanual response modes were similar in magnitude (3.03%, 3.22%, and 2.88%, respectively). PE was lower for the up–right/down–left mapping (2.13%) than for the up–left/down–right mapping (2.87%), $F(1, 92) = 5.15$, $p = .0256$, $MSE = 20.20$. This mapping effect interacted with the response mode, $F(3, 92) = 2.84$, $p = .0422$, $MSE = 20.20$. The vocal, bimanual, and left-hand unimanual response modes showed 0.22%, 0.89%, and 2.19% up–right/down–left advantages, respectively, but the right-hand unimanual response mode showed a 0.35% up–left/down–right advantage.

The Mapping × Stimulus-Set Location interaction was significant, too, $F(1, 92) = 8.89$, $p = .0037$, $MSE = 6.97$. Consistent with the RT data, the up–right/down–left advantage was larger when the stimulus set was on the left (0.40%) than when it was on the right (0.17%). The interaction of response with stimulus-set location was significant, $F(1, 92) = 15.75$, $p < .0001$, $MSE = 8.51$, indicating that a Simon effect also occurred in the PE data: For the right stimulus set the right response (2.02%) was more accurate than the left response (2.82%), but for the left stimulus set the left response (2.14%) was more accurate than the right response (3.01%). However, these two interactions did not interact with response mode, *F*s(3, 92) < 1.34, *p*s > .2678.

Discussion

The main purpose of Experiment 1 was to answer two questions: (a) Does stimulus-set location provide a frame of reference for representing relative response position, thus affecting orthogonal SRC; and (b) is the effect of this reference frame on orthogonal SRC similar across response modes? The orthogonal SRC effect was influenced by the location of the stimulus set in the manner predicted by the multiple asymmetric codes account. Regardless of the response mode, the magnitude of the up–right/down–left advantage was greater when the stimulus set was on the left side of the screen (and the response position was right relative to it) than when it was on the right side (and the response position was left relative to it). This pattern of results for the orthogonal SRC effect is in agreement with the hypothesis that the response set is represented as left or right relative to the stimulus set, with the response code that corresponds with this representation being positive and the one that does not being negative.

Also, as the multiple asymmetric codes account also predicts, an overall up–right/down–left advantage was evident, which did not vary significantly across response modes, and all response modes showed similar influences of display location on orthogonal SRC. These results imply that the orthogonal SRC effects obtained with different response modes are due to similar underlying mechanisms. The results are inconsistent with the end-state comfort account because the magnitude of the orthogonal SRC effect varied without any change of hand position or response position in the unimanual response modes, and qualitatively similar effects of stimulus-set location were obtained for the bimanual keypress and vocal response modes, to which the end-state comfort account does not apply. A question that might be asked is why for vocal responses, for which there is no mechanical operation of a switch at a specific location, response position would be represented as it is for manual responses. The answer is that both the microphone into which the utterances were spoken and the location from which they were emitted were positioned relative to the display.

The up–right/down–left advantage was largest for left-hand unimanual responses (32 ms; 2.19%) and smallest for right-hand unimanual responses (5 ms; −0.35%). The other two response modes showed similar sizes of up–right/down–left advantages (11 ms and 0.22% in the vocal response mode and 10 ms and 0.89% in the bimanual response mode). As noted, this ordering of effect magnitudes is in agreement with previous findings and consistent with the proposition that, for unimanual responses, the response hand provides an additional frame of reference for coding response position (Cho & Proctor, 2002). When the switch is to the left of the main part of the hand (i.e., for unimanual responses made with the right hand), the salience of the left response code is increased, weakening the up–right/down–left advantage; when the switch is to the right of the main part of the hand (i.e., for unimanual responses made with the left hand), the salience of the right response code is increased, strengthening the up–right/down–left advantage.

Finally, a Simon effect occurred, with the responses faster and more accurate when the locations of the stimulus set and response corresponded than when they did not. This Simon effect did not interact with the orthogonal SRC effect, suggesting that the two effects are distinct. Although this Simon effect is due to correspondence along the same dimension (horizontal) and not to correspondence of asymmetric codes across orthogonal dimensions, the fact that it does not interact with the orthogonal SRC effect is in agreement with the general proposition that overall performance reflects the summed contributions of activation produced by different frames of reference.

EXPERIMENT 2

Experiment 1 produced two effects that can be attributed to coding processes. The up–right/down–left advantage was larger with the left stimulus set than the right stimulus set, in agreement with the hypothesis that response position is represented relative to the stimulus set. Also, a Simon effect for stimulus set position occurred, indicating that a spatial code for stimulus-set location activated the corresponding response code. If these two effects are due to distinct codes, then it should be possible to dissociate the effects. One possible way to produce a dissociation is to vary the SOA between the fixation row and the imperative stimulus. The standard visual Simon effect decreases when responses are delayed relative to the onset of stimulus-location information (Hommel, 1994), a finding that is attributed to dissipation of the activation produced by the irrelevant stimulus location. The Simon effect for stimulus-set location likewise should be larger at short SOAs than at long SOAs since stimulus-set location is irrelevant. In contrast, because the representation of the response set is relevant to the intentional act of response selection that is to be performed, the influence of stimulus-set location on the orthogonal SRC effect should not vary as a function of SOA.

Method

Participants

A total of 96 new undergraduate students from the same pool as that in Experiment 1 participated and were randomly assigned to the four different response mode groups. As in that experiment, all participants were right handed and had normal or corrected-to-normal vision.

Stimuli, apparatus, and procedure

The method was similar to that in Experiment 1, with the following exceptions. A different toggle switch was used for the unimanual response modes. The switch was mounted on a panel (43 × 17.5 × 6 cm) interfaced with a MEL 2 response box. The height of the toggle switch was 7.5 cm. The imperative stimulus, an uppercase "X", appeared 2 cm above or below the fixation point 50, 200, 350, 500, or 650 ms after the onset of the fixation row "+ + +", which appeared to the left or right side of the screen. Unlike in the previous experiment, the asterisk for the next trial came on 1,250 ms after the response. Each participant performed 20 practice trials and two 100-trial blocks for each mapping condition, with a 1-min rest interval between them. Within each block, SOA varied randomly from trial to trial. A 2-min rest interval was given between mapping conditions.

Results

A total of 1.15% of the trials was removed as outliers. Mean RT and PE were calculated for each participant and analysed as in Experiment 1 with the additional within-subjects factor of SOA (see Table 2).

TABLE 2
Mean reaction time[a] and percentage of error in Experiment 2 as a function of mapping, location of stimulus set, SOA, and response mode

	Stimulus-set location													
	Left						*Right*							
	Up–left/ down–right		*Up–right/ down–left*		*Mapping effect*[b]		*Up–left/ down–right*		*Up–right/ down–left*		*Mapping effect*		*Corr. effect*[c]	
Mode	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*
50-ms SOA														
Vocal	563	1.25	540	0.63	23	0.62	542	1.46	534	1.50	8	−0.04	7	0.08
Bimanual	509	7.75	469	4.61	40	3.14	499	7.34	473	5.44	26	1.90	22	5.76
Right-hand	552	6.30	551	2.94	1	3.36	548	5.43	549	7.01	−1	−1.58	47	5.81
Left-hand	594	6.81	560	4.33	34	2.48	583	7.19	576	5.12	7	2.07	42	5.15
Mean	554	5.53	530	3.13	24	2.40	543	5.35	533	4.77	10	0.58	31	4.20
200-ms SOA														
Vocal	496	1.25	479	0.63	17	0.62	492	1.04	477	1.25	15	−0.21	7	0.00
Bimanual	451	6.94	416	3.13	35	3.81	435	4.19	416	4.05	19	0.14	17	0.25
Right-hand	523	3.56	486	3.61	37	−0.05	499	4.09	496	3.75	3	0.34	15	0.71
Left-hand	543	6.85	515	4.06	28	2.79	527	5.52	527	5.25	0	0.27	35	1.28
Mean	503	4.65	474	2.85	29	1.80	488	3.71	479	3.58	9	0.13	18	0.56
350-ms SOA														
Vocal	460	1.71	446	0.67	−6	1.04	453	1.88	435	1.46	18	0.42	3	0.50
Bimanual	410	6.78	385	3.54	25	3.24	415	4.07	386	2.08	29	1.99	10	1.88
Right-hand	482	3.41	471	3.57	11	−0.16	478	3.45	482	3.75	−4	−0.30	8	0.92
Left-hand	515	5.39	492	3.03	23	2.36	491	6.48	494	4.07	−3	2.41	21	1.67
Mean	467	4.32	448	2.70	19	1.62	459	3.97	449	2.85	10	1.12	10	1.24
500-ms SOA														
Vocal	448	1.25	422	1.04	26	0.21	433	0.63	423	1.90	10	−1.27	5	0.33
Bimanual	400	4.79	379	3.13	21	1.66	402	4.50	383	4.86	19	−0.36	20	0.26
Right-hand	479	3.40	460	3.17	19	0.23	458	2.34	458	2.75	0	−0.41	21	1.42
Left-hand	503	6.56	473	2.96	30	3.60	508	4.65	491	2.41	17	2.24	11	0.79
Mean	458	4.00	434	2.58	24	1.42	450	3.03	439	2.98	11	0.05	12	0.70
650-ms SOA														
Vocal	439	1.46	420	0.00	−1	1.46	428	1.04	419	0.83	9	0.21	7	0.63
Bimanual	405	3.75	374	2.55	31	1.20	400	1.67	381	2.50	19	−0.83	13	−0.23
Right-hand	459	4.19	451	4.19	8	0.00	476	2.37	456	2.76	20	−0.39	12	1.24
Left-hand	506	5.39	471	1.09	35	4.30	497	5.04	483	2.41	14	2.63	6	0.07
Mean	452	3.70	429	1.96	23	1.74	450	2.53	435	2.13	15	0.40	10	0.43

Note: Right-hand denotes the right-hand unimanual response mode, and left-hand denotes the left-hand unimanual response mode.

[a] In ms.

[b] Magnitude of the up–right/down–left advantage.

[c] Magnitude of the correspondence effect between the location of stimulus set and response.

Reaction time. The main effect of response mode was significant, $F(3, 92) = 7.97$, $p < .0001$, $MSE = 208{,}560$. RT was faster with bimanual keypresses ($M = 419$ ms) than with vocal and left- or right-unimanual responses (Ms = 468, 517, and 491 ms, respectively). The main effect of SOA was significant, too, $F(4, 368) = 498.00$, $p < .0001$, $MSE = 2{,}955$. RT became shorter as SOA increased, being 540, 486, 456, 445, and 442 ms at the 50-, 200-, 350-, 500-, and 650-ms SOAs, respectively. SOA interacted with response mode, $F(12, 368) = 2.58$, $p = .0027$, $MSE = 2{,}955$. The effect of SOA was greater in the vocal response mode (118 ms) than in the other modes (98, 89, and 89 ms for bimanual, and right and left unimanual responses, respectively). Right responses ($M = 471$ ms) were faster than left responses ($M = 477$ ms), $F(1, 92) = 6.05$, $p = .0157$, $MSE = 5{,}610$. The three-way interaction of Response × SOA × Response Mode was significant, $F(12, 368) = 1.83$, $p = .0422$, $MSE = 1{,}688$. With left-hand unimanual responses, RT was faster for left responses than for right responses when an imperative stimulus appeared 200 ms or 350 ms after the onset of the positional fixation point. With bimanual responses, RT was faster for left responses than for right responses when the SOA was 650 ms. Except for those conditions, the right responses were faster than the left responses.

The main effect of mapping was significant, $F(1, 92) = 9.61$, $p = .0026$, $MSE = 30{,}521$. RT was 17 ms shorter for the up–right/down–left mapping ($M = 465$ ms) than for the up–left/down–right mapping ($M = 482$ ms). As in Experiment 1, this mapping effect did not interact significantly with response mode, $F(3, 92) < 1.0$, but mapping interacted with stimulus-set location, $F(1, 92) = 21.08$, $p < .0001$, $MSE = 1{,}832$, and the three-way interaction of these variables with response mode was not significant, $F(3, 92) = 1.57$, $p = .2024$, $MSE = 1{,}832$. The up–right/down–left advantage was larger when the stimulus set was presented on the left side (24 ms) than when it was presented on the right side (11 ms). Most important, the effect of the stimulus-set location on the up–right/down–left advantage did not interact with the SOA, $F(4, 368) < 1.0$ (see Figure 2).

The interaction between response and stimulus-set location was significant, $F(1, 92) = 68.84$, $p < .0001$, $MSE = 3{,}581$. RT was 16 ms shorter when the response corresponded to the location of the stimulus set than when it did not. This Simon effect interacted with response mode, $F(3, 92) = 3.56$, $p = .0172$, $MSE = 3{,}581$. Only a 6-ms Simon effect occurred with vocal responses, whereas 16-, 21-, and 21-ms Simon effects were found with the bimanual and right- and left-unimanual responses. The Simon effect interacted with SOA, too, $F(4, 368) = 8.54$, $p < .0001$, $MSE = 1{,}783$ (see Figure 3), being greater at the 50-ms SOA (31 ms) than at the other SOAs (18, 10, 12, and 10 ms for the 200-, 350-, 500-, and 650-ms SOAs, respectively). The influence of SOA on the Simon effect differed with response mode, $F(12, 368) = 3.04$, $p = .0004$, $MSE = 1{,}783$. The SOA effect was smaller for vocal responses (5 ms) than for the other response modes (12 ms, 39 ms, and 36 ms for the bimanual, and right-hand and left-hand unimanual responses, respectively). There were no other significant main effects or interactions.

Percentage of error. Overall PE was 3.52%. The main effect of response mode was significant, $F(3, 92) = 5.73$, $p = .0012$, $MSE = 443.43$. As in Experiment 1, a post hoc Scheffe test showed that PE was lower with vocal responses (1.14%) than with the other response modes, and that bimanual and left- and right-hand unimanual responses were not different from each other (4.38%, 4.73%, and 3.80%, respectively). The SOA main effect was significant,

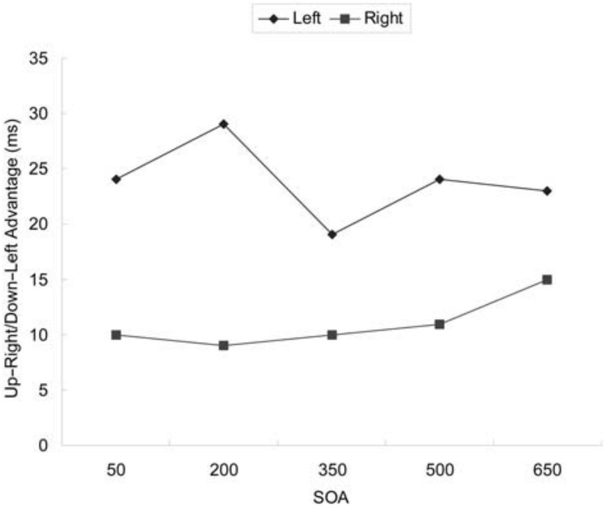

Figure 2. The up–right/down–left advantage as a function of stimulus-set location and SOA for reaction time in Experiment 2.

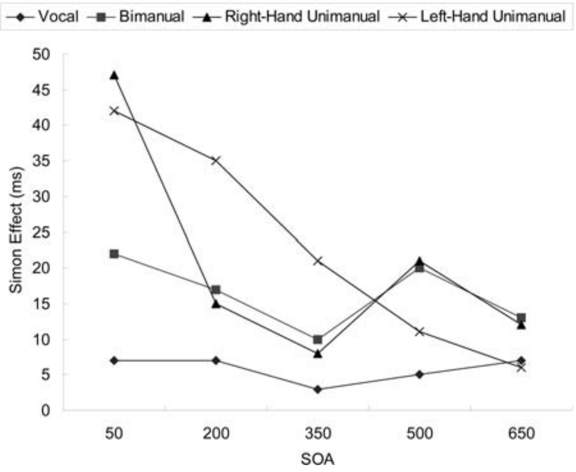

Figure 3. The Simon effect as a function of SOA and response mode for reaction time in Experiment 2.

$F(4, 368) = 12.50$, $p < .0001$, $MSE = 37.53$. PE became lower as SOA increased, being 4.69%, 3.70%, 3.46%, 3.15%, and 2.58% at the 50-, 200-, 350-, 500-, and 650-ms SOAs, respectively. However, SOA interacted with response mode, $F(12, 368) = 1.95$, $p = .0275$, $MSE = 37.53$. Unlike the RT data, the effect of SOA was smallest in the vocal response mode. That is, SOA affected the vocal response mode the most in the RT data, but the least in the PE data.

The PE data showed a 1.13% up–right/down–left advantage, *F*(1, 92) = 11.75, $p = .0009$, *MSE* = 104.07. Mapping interacted with response mode, *F*(3, 92) = 2.97, $p = .0360$, *MSE* = 104.07. The up–right/down–left advantage was 0.31%, 1.59%, 0.10%, and 2.52% in vocal, bimanual and right-hand and left-hand unimanual response modes. The interaction between mapping and stimulus-set location was significant, *F*(1, 92) = 8.11, $p = .0054$, *MSE* = 52.93, and this interaction pattern did not differ across response modes, *F*(3, 92) < 1.0. The up–right/down–left advantage was 1.8% when the stimulus set was on the left side of the screen and 0.46% when it was on the right side. Most important, SOA did not affect the interaction between mapping and stimulus-set location, *F*(4, 92) < 1.0, as in RT data.

A 1.43% Simon effect between the location of the stimulus set and response occurred, *F*(1, 92) = 32.32, $p < .0001$, *MSE* = 60.21. Although its effect size was smaller for the vocal response mode (0.31%) than for the other response modes (1.58%, 2.02%, and 1.79% for the bimanual, and right- and left-hand unimanual response modes, respectively), the three-way interaction among the location of the stimulus set, response, and response mode was not significant, *F*(3, 92) = 2.34, $p = .0783$, *MSE* = 60.21. The Simon effect interacted with SOA, *F*(4, 368) = 13.08, $p < .0001$, *MSE* = 36.74, being 4.16%, 0.56%, 1.24%, 0.7%, and 0.46% at the 50-, 200-, 350-, 500-, and 650-ms SOAs, respectively. This pattern was found in all but the vocal response mode, *F*(12, 368) = 2.00, $p = .0232$, *MSE* = 36.74, for which the Simon effect occurred only when the SOA was at least 350 ms (0.08%, 0%, 0.50%, 0.33%, and 0.63% for the 50-, 200-, 350-, 500-, and 650-ms SOAs, respectively).

Discussion

As in the previous experiment, the up–right/down–left advantage was found for all response modes in the RT and PE data. The advantage was larger with the left-hand (19 ms in RT and 2.52% in PE) than with the right-hand (9 ms and 0.10%) unimanual responses, even though this difference was significant only in the PE data. Consistent with prior experiments, this difference between the two unimanual response modes probably reflects an influence of coding the response apparatus relative to the response hand on the relative salience of response codes (Cho & Proctor, 2002). The fact that no other terms involved with mapping interacted with response mode shows that the orthogonal SRC effect is modulated by central factors, not by motoric factors.

The RT and PE data showed an influence of stimulus-set location on the up–right/down–left advantage across all response modes. As in Experiment 1, the advantage was greater when the stimulus set was presented on the left side of the screen than on the right side. Moreover, the influence of stimulus-set location on the orthogonal SRC effect did not interact with the SOA between the fixation row and the imperative stimulus. The spatial correspondence between the location of the stimulus set and the response position also influenced RT (16 ms) and PE (1.43%) in all response modes. Although this Simon effect interacted with the response mode only in RT, both the RT and PE data showed the smallest Simon effect in the vocal response mode (6 ms in RT and 0.31% in PE). In the other response modes, the size of the Simon effect did not differ significantly. This result is consistent with the results of other studies (e.g., Wang & Proctor, 1996), and it suggests that the spatial correspondence effect is influenced by the compatibility between stimulus and response sets.

Because this set-level compatibility between spatial stimuli and vocal responses is smaller than the others, the smallest Simon effect occurred in the vocal response mode.

Most important, unlike the orthogonal S–R mapping preference, the Simon effect interacted with SOA. The RT and PE data show that the Simon effect was greatest when the imperative stimulus was presented 50 ms after the onset of the irrelevant spatial information transmitted by the fixation row. With longer delays, the influence of the irrelevant spatial information decreased rapidly for all but the vocal response mode, which showed little effect at any interval. The result that the Simon effect interacted with the temporal interval between onsets of the fixation row and the imperative stimulus, but the orthogonal S–R mapping preference did not, suggests that underlying mechanisms producing the two kinds of SRC effect are different. Moreover, the relative response location seems to influence the processes causing the orthogonal SRC effect, whereas the location of the stimulus set seems to influence the processes causing the Simon effect.

EXPERIMENT 3

In Experiments 1 and 2, the up–right/down–left advantage was greater when the stimulus set appeared on the left side of the screen than when it appeared on the right, suggesting that the size of the orthogonal SRC effect is influenced by the response location relative to the stimulus set. However, unlike manipulations of response location, which change the direction of the orthogonal mapping preference (e.g., Michaels & Schilder, 1991), the up–right/down–left advantage did not shift to an up–left/down–right advantage when the stimulus set was to the right of the response location. A methodological difference is that stimulus-set location was varied within trial blocks in Experiments 1 and 2, whereas response location was held constant within trial blocks in studies of the response eccentricity effect. Thus, the influence of stimulus-set location on the orthogonal mapping preference in Experiments 1 and 2 may have been weaker than the typical response eccentricity effect because stimulus-set location was not fixed relative to the response location. Also, the display screen on which the stimuli were presented was always aligned with the response apparatus, whereas in studies of the response eccentricity effect, it is not. One purpose of Experiment 3 was to measure the effect of response location relative to stimulus-set location as a between-block variable, varying the location of the display screen relative to the response apparatus.

In all experiments showing the response eccentricity effect (i.e., a larger up–right/down–left advantage in the right hemispace than at midline and an up–left/down–right advantage in the left hemispace; Cho & Proctor, 2002; Michaels, 1989; Michaels & Schilder, 1991; Proctor & Cho, 2003; Weeks et al., 1995), only response location relative to the body midline was varied, and the spatial relation between the stimulus set and body midline was fixed at the middle response location. For this reason, Lippa and Adam (2001) concluded that hand position relative to the response device and the body midline determines the orthogonal mapping preference. However, in those studies, the response locations relative to the body midline were confounded with the response locations relative to the location of the stimulus set. Thus, a second purpose of Experiment 3 was to separate the effects of these two referents and to investigate whether the response eccentricity effect occurs when response location varies with respect to either the body midline or the location of the stimulus set.

Responses were made at three locations (left, centre, and right response positions) in two conditions. In the stimulus-set referent condition, the response location varied relative to the location of the stimulus set, but the responses were made at the body midline for all response locations. In the body-midline referent condition, the hand position was varied relative to the body midline, but the response location and the location of the stimulus set varied together, and responses were made at ipsilateral, body midline, and contralateral locations. In both conditions, "left"–"right" bimanual keypresses or unimanual toggle-switch movements were made in response to "up"–"down" stimuli. The vocal response mode was not included because the location of the response position could not be manipulated without changing the location of body midline.

If response location relative to the stimulus set is only one factor contributing to the response eccentricity effect, then, as in Experiments 1 and 2, for the stimulus-set referent condition the orthogonal SRC effect should not reverse to an up–left/down–right advantage when the stimulus set is to the right. In addition, there should be an effect of response location relative to the body midline in the body-midline referent condition. However, if the smaller effect of response location relative to the location of the stimulus set in Experiments 1 and 2 was due to the use of a within-block manipulation and/or the display screen being aligned with the response device, then the direction of the orthogonal mapping preference should reverse in the stimulus-set referent condition. Additionally, according to the multiple asymmetric codes account, these effects of response location on the orthogonal mapping preference should not differ across response modes.

For the end-state comfort account, hand position relative to body midline is the most important factor determining the orthogonal mapping preference. Consequently, the response eccentricity effect should occur only in the body-midline referent condition. The end-state comfort account again does not make any prediction for the bimanual response mode.

Method

Participants

A total of 72 new students from the same pool as that in Experiments 1 and 2, and meeting the same restrictions, participated in partial fulfilment of a course requirement. They were randomly assigned to the three different response modes: bimanual keypress, and left- and right-hand unimanual toggle switch movements.

Apparatus, stimuli, and procedure

The same apparatus was used as that in Experiment 2. In both conditions, an imperative stimulus, standard uppercase "X", appeared approximately 2 cm above or below the fixation row, which was presented at the centre of the screen, 500 ms after its onset. Both fixation row and imperative stimulus remained on the screen until a response was made. The fixation row for the next trial came on 1 s after the response or tone. Each participant performed 10 practice trials and three 50-trial blocks for each mapping condition, with a 30-s rest interval between them. A 2-min rest interval was given between mapping conditions.

Half the participants in each response-mode group performed the first three blocks with the up–left/down–right mapping and the next three blocks with the up–right/down–left mapping. The other half performed in the opposite order. For half the participants using each response mode, the response

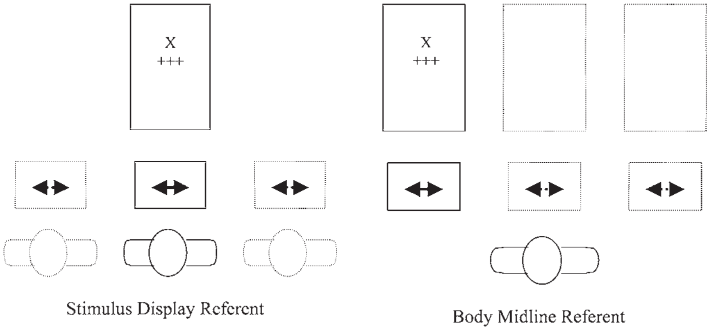

Figure 4. The left panel shows a top view of the physical arrangement for the stimulus-set referent condition, and the right panel shows a top view of the physical arrangement for the body midline referent condition in Experiment 3. For both panels, the solid figures designate one of the three positions of the display, response apparatus, and participant. The dotted figures represent the remaining two positions.

location was determined in terms of the location of the stimulus set (the stimulus-set referent condition), and for the other half, it was determined in terms of the body midline (the body-midline referent condition). Responses were collected at three different locations: left, centre, and right. Half of the participants began at the right response location and progressed to the left for both mappings. The other half began at the left response location and progressed to the right. The response locations were separated by 30-cm distance.

In the stimulus-set referent condition, the response location and the body midline of participants was determined in terms of the midline of the computer monitor (see Figure 4). At the beginning of each block, participants aligned their body midline with the response switch in the two unimanual response groups or with the centre of the two response keys in the bimanual keypress group by moving their chair. Thus, the location of the display screen remained the same for all response locations, as did the hand position relative to the participant's body midline. In the body-midline referent condition, the response location, as well as the location of the stimulus set, was determined in terms of the participant's body midline. At the beginning of each block, participants aligned their body midline with an arrow mark depicted on the table. The locations of the response apparatus and the computer monitor were determined in terms of this arrow position. Thus, the response apparatus position relative to the location of the stimulus set remained the same in all response locations. When the monitor was placed in the left or right location, participants were allowed to turn their head to see it, but not to turn their body toward it.

Results

A total of 0.47% of the trials were excluded as outliers. Mean RT and PE were calculated for each participant as a function of mapping (up–right/down–left, up–left/down–right), response (left, right), and switch location (left, centre, right). ANOVAs were conducted on the RT and PE data, with those variables as within-subject factors and response mode and reference point (stimulus set, body midline) as between-subject variables (see Table 3).

Reaction time. The main effect of response mode was significant, $F(2, 66) = 22.52$, $p < .0001$, $MSE = 37{,}495$. RT was shorter with bimanual keypresses ($M = 310$ ms) than

TABLE 3

Mean reaction time[a] and percentage of error in Experiment 3 as a function of mapping, switch location, referent point, and response mode

	Switch location																	
	Left						*Centre*						*Right*					
	Up–left / down–right		*Up–right / down–left*		*Mapping effect*[b]		*Up–left / down–right*		*Up–right / down–left*		*Mapping effect*[b]		*Up–left / down–right*		*Up–right / down–left*		*Mapping effect*[b]	
Mode	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*
							Stimulus display											
Bimanual	299	1.68	320	2.17	−21	−0.49	306	2.68	310	0.50	−4	2.18	318	3.17	302	0.83	16	2.34
Right-hand	419	1.68	438	3.69	−19	−2.01	437	3.20	417	2.18	20	1.02	468	5.27	418	1.33	50	3.94
Left-hand	405	1.73	422	3.16	−17	−1.43	410	3.01	412	1.83	−2	1.18	431	3.22	400	1.84	31	1.38
Mean	374	1.70	393	3.01	−19	−1.31	384	2.96	380	1.50	4	1.46	406	3.89	373	1.34	33	2.55
							Body midline											
Bimanual	319	3.34	313	3.68	6	−0.34	312	1.85	296	2.17	16	−0.32	315	2.17	311	2.83	4	−0.66
Right-hand	396	2.51	399	3.03	−3	−0.52	389	2.84	385	2.19	4	0.65	388	3.54	362	1.33	26	2.21
Left-hand	391	2.01	354	1.83	37	0.18	395	1.66	353	1.33	42	0.33	421	2.17	368	0.84	53	1.33
Mean	369	2.62	355	2.85	14	−0.23	365	2.12	345	1.90	20	0.22	375	2.63	347	1.67	28	0.96

Note: Right-hand denotes the right-hand unimanual response mode, and left-hand denotes the left-hand unimanual response mode.

[a] In ms.

[b] Magnitude of the up–right/down–left advantage.

with right-hand ($M = 410$ ms) and left-hand ($M = 397$ ms) unimanual responses. Right responses ($M = 369$ ms) were faster than the left responses ($M = 376$ ms), $F(1, 66) = 8.84$, $p = .0041$, $MSE = 1{,}251$. Although the mean RT was shorter for the body-midline referent condition ($M = 359$ ms) than for the stimulus-set referent condition ($M = 386$ ms), the main effect of the reference point was not significant, $F(1, 66) = 3.93$, $p = .0545$, $MSE = 37{,}495$. The three-way interaction of reference point, switch location, and response mode was significant, $F(4, 132) = 4.32$, $p = .0026$, $MSE = 1{,}306$. In the stimulus-set referent condition, RT did not differ across the switch locations in all response modes. However in the body-midline referent condition, RT was fastest when the switch was placed at the ipsilateral location and slowest when it was placed at the contralateral location for the two unimanual response modes ($M = 397$ ms, 387 ms, and 375 ms for the right-hand unimanual response mode and $M = 372$ ms, 374 ms, and 395 ms for the left-hand unimanual response mode at the left, centre, and right response locations, respectively). For bimanual keypresses, responses tended to be faster at the centre location than at the other locations (Ms = 316 ms, 304 ms, and 313 ms for the left, centre, and right locations, respectively).

The main effect of mapping was significant, $F(1, 66) = 8.73$, $p = .0043$, $MSE = 4{,}350$, and a 13-ms up–right/down–left advantage was found. Mapping did not interact with response mode, $F(2, 66) = 1.86$, $p = .1631$, $MSE = 4{,}350$. The response eccentricity effect occurred, $F(2, 132) = 12.69$, $p < .0001$, $MSE = 1{,}537$. The up–right/down–left advantage was 30 ms at the right switch location and 13 ms at the centre switch location, but -2 ms at the left switch location. Most important, the three-way interaction of reference point, mapping, and switch location was significant, $F(2, 132) = 4.03$, $p = .0199$, $MSE = 1{,}537$ (see Figure 5), and the interaction with response mode was not, $F(4, 132) < 1.0$. In the stimulus-set referent condition, the response eccentricity effect occurred (up–right/down–left advantages of 33 ms, 4 ms, and -19 ms at the right, centre, and left response locations, respectively), $F(2, 132) = 15.51$, $p < .0001$, $MSE = 1{,}537$. However, in the body-midline referent condition, the corresponding advantages were 28 ms, 20 ms, and 13 ms, and this 15 ms response eccentricity effect was not significant, $F(2, 132) = 1.21$, $p = .3005$, $MSE = 1{,}537$. That is, the response eccentricity effect unambiguously occurred when the referent point for the response locations was the location of the stimulus set, but not when it was the body midline.

Unlike the previous experiments, the interaction between switch location and response was not significant, $F(2, 132) < 1.0$. That is, there was no Simon effect of the irrelevant spatial information on the RT. No other main effect or interaction was significant.

Percentage of error. Overall PE was 2.35%, and PE did not differ significantly across response modes, $F(2, 66) = 1.04$, $p = .3576$, $MSE = 33.47$. The right responses (1.98%) were more accurate than the left responses (2.71%), $F(1, 66) = 10.65$, $p = .0017$, $MSE = 10.93$.

The PE was lower with the up–right/down–left mapping (2.04%) than with the up–left/down–right mapping (2.65%), but the main effect of mapping was not significant, $F(1, 66) = 3.66$, $p = .0601$, $MSE = 21.86$. Mapping did not interact with the response mode, $F(2, 66) < 1.0$, but it did with response, $F(1, 66) = 6.77$, $p = .0115$, $MSE = 7.95$. The up–right/down–left advantage was 0.95% with right responses, but only 0.11% with left responses.

The response eccentricity effect was found, $F(2, 132) = 12.63$, $p < .0001$, $MSE = 9.30$. A 1.76% up–right/down–left advantage occurred at the right switch location, but it was reduced to 0.84% at the centre location and reversed to a 0.77% up–left/down–right advantage at

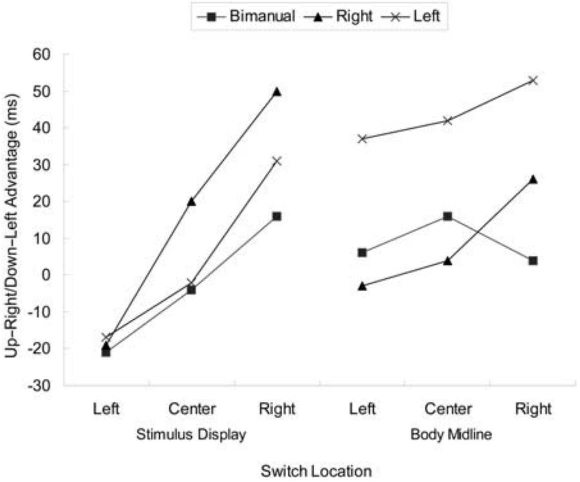

Figure 5. The up–right/down–left advantage as a function of response location, referent point, and response mode for reaction time in Experiment 3.

the left location. As in the RT data, the response eccentricity effect was more evident in the stimulus-set referent condition than in the body-midline referent condition, $F(2, 132) = 4.08$, $p = .0190$, $MSE = 9.30$. In the stimulus-set referent condition, the up–right/down–left advantage was 2.55%, 1.46%, and −1.31% at the right, centre, and left switch locations, respectively, $F(2, 132) = 15.32$, $p < .0001$, $MSE = 9.30$, but when the body midline served as a referent point for them, it was 0.96%, 0.22%, and −0.23%, $F(2, 132) = 1.39$, $p = .2536$, $MSE = 9.30$. This term did not interact with response mode, $F(4, 132) < 1.0$. No other terms were significant.

Discussion

Experiment 3 provides additional evidence that the orthogonal SRC effect does not differ with response mode. The RT and PE data showed the same pattern of orthogonal SRC effect in all response modes, even though the magnitude of the up–right/down–left advantage differed slightly across the modes. This result implies that for all response modes the orthogonal mapping preference is caused by the same underlying mechanism.

Response location relative to the stimulus set was the most important factor determining the orthogonal mapping preference. When it was a between-block variable in this experiment, as in prior studies showing the response eccentricity effect, and hand position was fixed at the body midline, as in Experiments 1 and 2, the effect of response location relative to the stimulus set increased enough to change the direction of the orthogonal SRC effect. That is, a 19-ms and 1.31% up–left/down–right advantage was found at the left response location relative to the stimulus set, even though the location of the stimulus set relative to participants' body midline was right, whereas a 33-ms and 2.55% up–right/down–left advantage was found at the right response location. This result indicates that different orthogonal mapping preferences can be obtained without changing the motoric state of the responding hand.

The results show little effect on the orthogonal mapping preference of hand position relative to the body midline. When response location was determined in terms of the body midline, and its spatial relation with the stimulus-set location was fixed, the magnitude of the response eccentricity effect was smaller than when it was determined in terms of the location of the stimulus set. A 13-ms and −0.23% up–right/down–left advantage was found at the left response location, compared to a 20-ms and 0.22% up–right/down–left advantage at the centre response location and a 28-ms and 0.96% up–right/down–left advantage at the right response location. This result suggests, contrary to the end-state comfort account, that hand position relative to the body midline is less important than response location relative to the location of the stimulus set in determining the direction of the orthogonal mapping preference. Even though this effect did not interact with response mode, the two unimanual response modes tended to show the response eccentricity effect (29 ms and 2.72%, and 16 ms and 1.15% response eccentricity effects for the left- and right-hand unimanual response modes, respectively), unlike the bimanual response mode (6 ms and −0.34% at the left response location, 16 ms and −0.32% at the centre response location, and 4 ms and −0.66% at the right response location).

Although the location of the stimulus set relative to the body midline differed across response locations in both conditions, there was no correspondence effect (i.e., Simon effect) between the location of the stimulus set relative to the body midline and the response position. This lack of effect was due to the fact that the location of the stimulus set was constant in a block, rather than varying, as in Experiments 1 and 2. This result is consistent with those of Experiment 2 in implying that the orthogonal SRC effect is independent of the Simon effect.

GENERAL DISCUSSION

All three experiments showed the first type of orthogonal SRC effect identified by Lippa and Adam (2001), a statistically significant overall advantage for the up–right/down–left mapping over the alternative mapping. This advantage was evident numerically for each response mode in every experiment, and only for the PE data in Experiment 2 did it interact significantly with response mode. Across Experiments 1 and 2, which included all response modes, the up–right/down–left advantage for RT was 14 ms with vocal responses, 19 ms with bimanual keypresses, and 17 ms with unimanual switch movements.

The fact that the up–right/down–left advantage was evident for all response modes is in agreement with Weeks and Proctor's (1990) proposal that it reflects a tendency to code up and right as the polar referents of the dimensions, regardless of the display and response formats. This leads to a benefit for the up–right/down–left mapping, which maintains the polar relations of the stimuli and responses, compared to the up–left/down–right mapping, which reverses the relations. Umiltà (1991) and Adam et al. (1998) argued that this coding asymmetry is restricted to verbal codes and thus should be larger when the stimulus or response set is verbal. The finding that the up–right/down–left advantage was, if anything, slightly smaller for the verbal, vocal response mode than for the manual response modes is counter to what their dual-strategy hypothesis predicts. This finding and others

(Cho & Proctor, 2001; Proctor & Cho, 2001) suggest that it is unlikely that the overall up–right/down–left advantage is closely linked to verbal codes.

Experiments 1 and 2 showed that when stimulus-set location varies along the same dimension as the responses, the orthogonal SRC effect changes in the manner expected from the response position being coded relative to the stimulus set: The up–right/down–left advantage was larger when the stimulus set appeared on the left side of the screen than when it appeared on the right side for all response modes. That stimulus-set location influenced the orthogonal SRC effect cannot be explained by the end-state comfort account because responses were made at body midline, and end-state comfort remained constant across stimulus-set locations. The specific effect of stimulus-set location on orthogonal SRC is in agreement with the prediction of the multiple asymmetric codes account that stimulus-set location should influence performance through providing a referent relative to which response position is coded. This outcome is consistent with previous results found with an inactive response device as a referent (Proctor & Cho, 2003; Weeks et al., 1995). Moreover, the finding that the effect of stimulus-set location did not interact significantly with response mode is also in agreement with the prediction that the manipulation should have a qualitatively similar effect on the vocal, bimanual keypress, and unimanual switch-movement response modes.

For Experiments 1 and 2, in which the left or right location of the stimulus set varied randomly from trial to trial, a Simon effect based on stimulus-set location was obtained: Performance was better when the stimulus-set location corresponded with the response location than when it did not. The presence of the Simon effect in those experiments indicates that stimulus-set location was coded spatially as left or right. In Experiment 2, this Simon effect was a decreasing function of the SOA between the fixation row designating stimulus-set side and the imperative stimulus. This result is consistent with those from several other studies of the Simon effect, in which the effect of irrelevant location information is most pronounced shortly after its onset and then diminishes (e.g., Hommel, 1993; Roswarski & Proctor, 1996).

Although the Simon effect for stimulus-set location decreased across SOA, the orthogonal SRC effect did not, and these two effects did not interact with each other. Also, when the location of the display was held constant within a trial block in Experiment 3, there was no Simon effect for stimulus-set location, but its location altered the orthogonal SRC effect as in Experiments 1 and 2. These results imply that the orthogonal SRC and Simon effects have different underlying mechanisms. Most accounts of the Simon effect attribute it to an automatic response-selection route (e.g., Hommel, 1997; Zorzi & Umiltà, 1995). When a stimulus containing spatial information occurs, a spatial code and codes representing other stimulus properties are produced. The spatial code for the stimulus activates its corresponding spatial response code through a long-term association in the automatic response-selection route. Even though the activated response code is irrelevant to the task, it produces a benefit or cost to performance based on whether or not it corresponds with the response activated by the relevant stimulus information. The response activation produced by the irrelevant spatial code lasts only a very short time (Danziger, Kingston, & Ward, 2001; Hommel, 1994), as was the case for the Simon effect for stimulus-set location in Experiment 2.

If this location code were responsible for the influence of stimulus-set location on the orthogonal SRC effect, this influence also should have decreased as SOA increased. That it did not provides further evidence that the effect of stimulus-set location on orthogonal SRC is not due to its coded location but to the coding of response location relative to the display. This effect most likely arises in intentional S–R translation processes instead of automatic response activation. We propose that only the response-relevant property of the stimulus specified by the instructed mapping is represented in the intentional translation route. Irrelevant stimulus properties, such as stimulus-set location, do not influence the intentional translation route. Because the code for stimulus-set location is activated only in the automatic response-selection route, it does not affect the asymmetric coding in the intentional translation route.

Experiment 3 showed the importance of response location relative to the stimulus set in the response eccentricity effect. When this relation was manipulated as a between-block variable, a large "response eccentricity effect" was obtained: The large up–right/down–left advantage evident when the response location was to the right of the stimulus set was reduced when it was centred, and reversed to an up–left/down–right advantage when the response location was to the left. Even though response location with respect to body midline was the same for the different locations relative to the stimulus set, the effect on the orthogonal mapping preference was almost identical to that obtained for the response eccentricity effect in previous studies (e.g., Cho & Proctor, 2002; Proctor & Cho, 2003). Moreover, hand position with respect to body midline had no significant effect on the mapping preference. Thus, the results support the prediction of the multiple asymmetric codes account that the primary influence on the orthogonal mapping preference comes from response location relative to the stimulus set and not, as predicted by the end-state comfort account, the hand position relative to body midline.

The results of Experiment 3 are in agreement with those of Experiments 1 and 2 in showing that the manipulation of stimulus-set location in the response dimension changed the orthogonal mapping preference consistently for the bimanual keypress and unimanual switch-movement response modes. This finding is in agreement with the hypothesis that response location is coded relative to stimulus-set location, with this spatial code increasing the salience of the corresponding response code and thus affecting the orthogonal mapping preference. The similarity of effect of stimulus-set location for all response modes provides evidence that the effect is not mainly a function of the state of the motor system.

Conclusion

The specific effects of stimulus-set location on orthogonal SRC in this study are those predicted from the proposition of the multiple asymmetric codes account that response position is coded relative to other objects—in this case, the stimulus set. The qualitatively similar pattern of results for all response modes and the finding that response eccentricity effect is due primarily to the response location relative to the display are also in agreement with the account.

Because the end-state comfort account is only applicable to the orthogonal SRC effects that vary as a function of hand and hand position, it must be assumed that this category of effects is distinct from the overall up–right/down–left advantage. However, the two kinds of effects are not mutually exclusive. In the present study, an overall up–right/down–left advantage and effects of response position were obtained in the same experiments. Also, there is no clear-cut boundary between the two effects, even though the account assumes that the underlying mechanisms are distinct. For example, Proctor and Cho (2003) found response eccentricity and relative response-location effects with bimanual keypresses similar to the effects found with unimanual responses. Because their results showed an effect of response position, these effects should be classified as the latter type of orthogonal SRC effect. However, because they occurred regardless of response mode, the effects should be classified as the first type of effect.

The results of the present experiments, along with those of other recent studies, imply that all orthogonal SRC effects are of similar nature, as assumed by the multiple asymmetric codes account. The effects are influenced by many variables, including response location, hand posture, and stimulus-set location, but there is no evidence to indicate that there are two fundamentally different types of orthogonal SRC effect. The asymmetric coding perspective is the only extant account that can explain the overall up–right/down–left advantage and the influences of hand, response position, and other variables on the orthogonal SRC effect. Unless much stronger evidence to the contrary is forthcoming, the overall up–right/down–left advantage and the orthogonal SRC effects that vary as a function of hand position should be regarded as a single category of phenomena amenable to explanations in terms of multiple spatial codes.

REFERENCES

Adam, J. J., Boon, B., Paas, F. G. W. C., & Umiltà, C. (1998). The up–right/down–left advantage for vertically oriented stimuli and horizontally oriented responses: A dual-strategy hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1582–1595.

Bauer, D. W., & Miller, J. (1982). Stimulus–response compatibility and the motor system. *Quarterly Journal of Experimental Psychology*, *34A*, 367–380.

Chase, W. G., & Clark, H. H. (1971). Semantics in the perception of verticality. *British Journal of Psychology*, *62*, 311–326.

Cho, Y. S., & Proctor, R. W. (2001). Effect of an initiating action on the up–right/down–left advantage for vertically arrayed stimuli and horizontally arrayed responses. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 472–484.

Cho, Y. S., & Proctor, R. W. (2002). Influences of hand posture and hand position on compatibility effects for up–down stimuli mapped to left–right responses: Evidence for a hand-referent hypothesis. *Perception & Psychophysics*, *64*, 1301–1315.

Cho, Y. S., & Proctor, R. W. (2003). Stimulus and response representations underlying orthogonal stimulus–response compatibility effects. *Psychonomic Bulletin & Review*, *10*, 45–73.

Danziger, S., Kingston, A., & Ward, R. (2001). Environmentally defined frames of reference: Their time course and sensitivity to spatial cues and attention. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 494–503.

Hommel, B. (1993). The role of attention for the Simon effect. *Psychological Research/Psychologische Forschung*, *55*, 208–222.

Hommel, B. (1994). Effects of irrelevant spatial S–R compatibility depend on stimulus complexity. *Psychological Research/Psychologische Forschung*, *56*, 179–184.

Hommel, B. (1997). Toward an action-concept model of stimulus–response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus–response compatibility* (pp. 281–320). Amsterdam: North-Holland.

Hommel, B., & Prinz, W. (Eds.). (1997). *Theoretical issues in stimulus–response compatibility*. Amsterdam: North-Holland.

Just, M. A., & Carpenter, P. A. (1975). The semantics of locative information in pictures and mental images. *British Journal of Psychology, 66,* 427–441.

Lippa, Y., & Adam, J. J. (2001). Orthogonal stimulus–response compatibility resulting from spatial transformations. *Perception & Psychophysics*, *63*, 156–174.

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.

Michaels, C. F. (1989). S–R compatibilities depend on eccentricity of responding hand. *Quarterly Journal of Experimental Psychology*, *41A*, 262–272.

Michaels, C. F., & Schilder, S. (1991). Stimulus–response compatibilities between vertically oriented stimuli and horizontally oriented responses: The effects of hand position and posture. *Perception & Psychophysics*, *49*, 342–248.

Olson, G. M., & Laxar, K. (1973). Asymmetries in processing the terms "right" and "left". *Journal of Experimental Psychology*, *100*, 284–290.

Proctor, R. W., & Cho, Y. S. (2001). The up-right/down-left advantage occurs for both participant-paced and computer-paced conditions: An empirical observation on Adam, Boon, Paas, & Umiltà (1998). *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 466–471.

Proctor, R. W., & Cho, Y. S. (2003). Effects of relative position and response eccentricity on orthogonal stimulus–response compatibility with joystick and keypress responses. *Quarterly Journal of Experimental Psychology*, *56A*, 309–327.

Proctor, R. W., & Reeve, T. G. (Eds.). (1990). *Stimulus–response compatibility: An integrated perspective*. Amsterdam: North-Holland.

Proctor, R. W., Wang, H., & Vu, K.-P. L. (2002). Influences of different combinations of conceptual, perceptual, and structural similarity on stimulus–response compatibility. *Quarterly Journal of Experimental Psychology*, *55A*, 59–74.

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 effect 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.

Umiltà, C. (1991). Problems of the salient-features coding hypothesis: Comment on Weeks and Proctor. *Journal of Experimental Psychology: General*, *120*, 83–86.

Wang, H., & Proctor, R. W. (1996). Stimulus–response compatibility as a function of stimulus code and response modality. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 1201–1217.

Weeks, D. J., & Proctor, R. W. (1990). Salient-features coding in the translation between orthogonal stimulus–response dimensions. *Journal of Experimental Psychology: General*, *119*, 355–366.

Weeks, D. J., Proctor, R. W., & Beyak, B. (1995). Stimulus–response compatibility for vertically oriented stimuli and horizontally oriented responses: Evidence for spatial coding. *Quarterly Journal of Experimental Psychology*, *48A*, 367–383.

Zorzi, M., & Umiltà, C. (1995). A computational model of the Simon effect. *Psychological Research*, *58*, 193–205.

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