THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2003, *56A* (2), 309–327

Effects of response eccentricity and relative position on orthogonal stimulus–response compatibility with joystick and keypress responses

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When unimanual left–right movement responses are made to up–down stimuli, performance is better with the up–right/down–left mapping when responding in the right hemispace and with the up–left/down–right mapping when responding in the left hemispace. We evaluated whether this response eccentricity effect is explained best in terms of rotational properties of the hand (the end-state comfort hypothesis) or asymmetric coding of the stimulus and response alternatives (the salient features coding hypothesis). Experiment 1 showed that bimanual keypresses yield a response eccentricity effect similar to that obtained with unimanual movement responses. In Experiment 2, an inactive response apparatus was placed to the left or right of the active response apparatus to provide a referent. For half of the participants, the active and inactive apparatuses were joysticks, and for half they were response boxes with keys. For both response types, an up–right/down–left advantage was evident when the relative position of the active response apparatus was right but not when it was left. That bimanual keypresses yield similar eccentricity and relative location effects to those for unimanual movements is predicted by the salient features coding perspective but not by the end-state comfort hypothesis.

For stimuli and responses that vary along parallel spatial dimensions, reaction time (RT) is faster when the mapping of stimuli to responses is spatially compatible than when it is not (e.g., Fitts & Deininger, 1954). Such stimulus–response compatibility (SRC) effects have been attributed to differences in the efficiency of a central stage of information processing, called response selection or stimulus–response translation, which operates on a spatial stimulus code to select a spatial response code (Hommel & Prinz, 1997; Proctor & Reeve, 1990). In an influential study, Bauer and Miller (1982) demonstrated that SRC effects also occur when the stimulus and response sets vary along orthogonal dimensions. They examined performance of two-choice tasks in which subjects responded by moving the index finger of a hand

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We would like to thank Iring Koch, Robert Logie, and two anonymous reviewers for their comments on earlier versions of this manuscript.

http://www.tandf.co.uk/journals/pp/02724987.html DOI:10.1080/02724980244000350

from a central home key to one of two target response keys. In their Experiment 1, the stimuli were left and right locations and the responses were up and down movements. Mapping preferences were obtained that varied as a function of hand: With the left hand, RT was 117 ms shorter for the left–up/right–down mapping than for the opposite mapping, but with the right hand, RT was 2 ms shorter (and 4% more accurate) for the right–up/left–down mapping than for the other mapping. In Bauer and Miller's Experiment 3, the stimuli were up and down locations, and the responses were left and right movements. In this case, both hands showed a preference for the up–right/down–left mapping, although the RT advantage for that mapping was smaller for the right hand than for the left hand.

Motor system accounts

Bauer and Miller (1982) explained their results in terms of motor factors, rather than cognitive coding factors, because of the apparent link between the SRC effects and the structure of the motor system. They assumed that when a stimulus occurs there is an implicit tendency to react toward that stimulus, and this implicit tendency combines with the explicit movement toward the response key to yield a rotational movement. They attributed the resulting SRC effects to the right hand preferring counter-clockwise rotational movements and the left hand clockwise rotational movements.

Michaels (1989) demonstrated that the orthogonal SRC effect is also influenced by response location. In her Experiment 1, subjects made unimanual left–right movement responses to up–down stimuli at three different locations for each hand: body midline and ipsilateral locations of 30 and 60 cm to the body midline. An up–right/down–left advantage was found at midline with each hand, as in Bauer and Miller's (1982) study. However, at the ipsilateral locations, the advantage increased for the right-hand responses but reversed for the left-hand responses. This effect of response location, called the response eccentricity effect (Lippa & Adam, 2001), is robust, having been replicated in several studies. Michaels and Schilder (1991, Experiment 1) showed that the eccentricity effect still occurred when subjects were forced to adopt the same hand posture at all locations. This was achieved by having them hold a block of wood, insert their index finger between two microswitches, and deflect the finger left or right in response to vertically arrayed stimuli. Also, Lippa and Adam obtained the response eccentricity effect when the responses were made behind the display, as well as in front of it.

Michaels (1989) noted that Bauer and Miller's (1982) movement preference explanation cannot explain the response eccentricity effect but concluded, "It seems clear, though, that Bauer and Miller are correct in asserting that the characteristics of the motor system figure significantly in the establishment of 'compatibilities'" (p. 271). She proposed an ecological hypothesis, closely related to Bauer and Miller's hypothesis, to explain the influence of response eccentricity on orthogonal SRC. According to the ecological hypothesis, the motor system is linked closely with the perception system, and "motor system variables can 'set up perception'" (p. 271). Michaels concluded that the hand positions associated with the different response locations set up the perception system, causing the different mapping preferences at the different locations.

Lippa and Adam (2001) recently proposed an explanation of the response eccentricity effect that they call the end-state comfort hypothesis. This hypothesis is a hybrid explanation in which the motor system determines the dimension along which responses are coded. We classify it here as a motor system account because it is closely related to the ideas of Michaels (1989) that the state of the action system determines relative compatibility, but “it not only rephrases these previous ideas, but also develops them further and specifies them” (Lippa & Adam, 2001, p. 172). According to the end-state comfort hypothesis, the image of the response hand or keys is mentally transformed or rotated clockwise or counter-clockwise to align the response dimension with the stimulus dimension. The direction of transformation is the one that would result in the most comfortable end-state position if the hand were actually rotated. With the hand in a prone posture, the left hand prefers a clockwise rotation and the right hand a counter-clockwise rotation at the body midline and ipsilateral response positions. These movement constraints are the source of the response eccentricity effect on orthogonal SRC. According to Lippa and Adam, whereas the ecological approach stresses the “state of the motor (action) system itself”, the end-state comfort hypothesis stresses “the action possibilities from the motor system” (p. 172). That is, the end-state comfort hypothesis assumes that the movement constraints in the given hand posture and position, rather than the hand posture itself, determine the orthogonal SRC effect.

From Bauer and Miller’s (1982) study to the present, the motor system accounts of orthogonal SRC effects have focused on situations in which the responses are unimanual aimed movements to target locations or unimanual switch movements. The idea that the structure or state of the motor system sets up perception—which runs through the movement preference, ecological, and end-state comfort hypotheses—arises from the fact that variables associated with the motor system, such as hand, hand posture, and response position, influence orthogonal SRC systematically. However, orthogonal SRC effects are obtained for a variety of situations in which the responses are bimanual discrete keypresses or vocal responses. When left–right responses are made to vertically arrayed stimuli, the up–right/down–left mapping usually yields better performance than the up–left/down–right mapping with bimanual keypresses (e.g., Adam, Boon, Paas, & Umiltà, 1998) and vocal “left”–“right” responses (e.g., Weeks & Proctor, 1990). The motor system accounts provide no explanations for these orthogonal SRC effects, and these effects must be explained in a different manner (Adam et al., 1998; Lippa & Adam, 2001).

Asymmetric coding accounts

Because of the widespread nature of orthogonal SRC effects, and because compatibility effects typically are attributed to the codes on which response selection is based (Hommel & Prinz, 1997; Proctor & Reeve, 1990), Weeks and Proctor (1990) proposed a coding explanation of the effects. Their explanation is based on the salient features coding principle developed by Proctor and Reeve (1985, 1986) to explain SRC and precueing effects obtained in four-choice tasks. This principle states that response selection is more efficient when the salient features of the stimulus and response sets correspond than when they do not. As applied to orthogonal two-choice tasks, the salient features coding hypothesis is that both the stimulus and response sets are coded asymmetrically, with responses being faster and more accurate for the mapping in which the more salient stimulus code is mapped to the more salient response code and the less salient stimulus code to the less salient response code than for the alternative mapping. Weeks and Proctor proposed a specific explanation for the commonly obtained up–right/down–left advantage based on findings indicating that “right” and “up” are more salient than “left” and “down” (Chase & Clark, 1971; Just & Carpenter, 1975; Olson & Laxar, 1973, 1974). As evidence to support this hypothesis, Weeks and Proctor (1990) showed that the up–right/down–left advantage occurs with vocal “left”–“right” responses, keypress responses, and unimanual aimed movements, and with arrow stimuli and physical location stimuli.

Umiltà (1991) offered a dual-strategy hypothesis as an alternative to the salient features coding hypothesis. This hypothesis retains the basic property of the salient features account in attributing the up–right/down–left advantage to asymmetric coding of the stimulus and response sets. However, it restricts this asymmetry to verbal codes. Adam et al. (1998) reported results of four experiments that they interpreted as support for the dual-strategy hypothesis: The up–right/down–left advantage was obtained when the trials were initiated by the participant but not when they were initiated by the computer, and the advantage was evident when a verbal precue specified the mapping but not when a spatial precue did. However, subsequent results have shown that (1) participant versus computer initiation is not a factor unless the initiating action corresponds with one of the response codes (Cho & Proctor, 2001; Proctor & Cho, 2001), and (2) the verbal–spatial precue distinction is not a crucial factor, whereas whether or not the precue specifies the complete mapping is (Kleinsorge, 1999). On the whole, the results are in closer agreement with the assumption of the salient features coding hypothesis that asymmetric coding is not restricted to verbal codes than with the assumption of the dual-strategy hypothesis that it is (Cho & Proctor, in press-b).

Although Weeks and Proctor (1990) placed emphasis on up and right as being salient, the more general idea behind the salient features coding principle is that salience is not a fixed property but varies as a function of several factors. For example, manipulations of grouping for the stimulus and response sets have been shown to affect the relative salience of pairs of locations in four-choice tasks (Reeve, Proctor, Weeks, & Dornier, 1992) and in two-choice tasks for which the stimulus and response locations vary along two dimensions (Vu & Proctor, 2002). Weeks, Proctor, and Beyak (1995) incorporated this aspect of salient features coding into the hypothesis developed by Weeks and Proctor for orthogonal SRC, proposing that the response eccentricity effect is a consequence of an increase in salience of the response code corresponding to the location of the response switch relative to the other response code. They reported two experiments to support this interpretation. In their Experiment 1, responses were collected at contralateral locations for each hand, as well as at body midline and ipsilateral locations, to dissociate responding hand and response location. For both left and right hands, the up–right/down–left advantage increased with increasing eccentricity to the right and reversed to an up–left/down–right advantage for eccentricities to the left.

The fact that the response eccentricity effect is a function of response location rather than the hand is directly predicted by the salient features coding hypothesis if, as hypothesized, salience varies with response location, and it is counter to Michaels’s (1989) ecological hypothesis that emphasizes hand position rather than response location. However, Lippa and Adam (2001) noted that the end-state comfort hypothesis can explain the independence of the eccentricity effect from the hand used to respond if it is assumed that the preferred direction of rotation at contralateral locations is opposite to that at ipsilateral locations. At the contralateral location, the fingertip, wrist, and forearm must be aligned to grasp the toggle switch, and the preferred movement is a clockwise rotation for the left hand and a counter-clockwise for the right hand. For this reason, the left-hand responses show an up–left/down–right advantage at the left hemispace and body midline and an up–right/down–left advantage at the right hemispace, and the right-hand responses show an up–right/down–left advantage at the right hemispace and body midline and an up–left/down–right advantage at the left hemispace.

In Weeks et al.'s (1995) Experiment 2, an inactive switch was placed to the left or right of the active switch, which was placed at body midline. Mapping interacted with the position of the inactive switch: An up–right/down–left advantage of 20 ms occurred when the active switch was located to the right of the inactive switch, and this changed to an up–left/down-right advantage of 8 ms when the active switch was located to the left of the inactive switch. This outcome was predicted by Weeks et al. based on the numerous results in the compatibility and spatial perception literatures indicating that location is coded relative to referent objects (Kosslyn, 1994; Umiltà & Nicoletti, 1990). In terms of the salient features coding hypothesis, when the active switch is coded as left relative to the inactive switch, the salience of the left response is increased. The increased salience of the left response results in elimination of the up–right/down–left advantage that is apparent when the active switch is coded as right. Note that this relative-location effect on orthogonal SRC cannot be explained by the end-state comfort hypothesis because the position of an inactive response switch should not influence the end-state comfort of the rotation alternatives for the hand grasping the active response switch. This is because the predictions for the end-state comfort hypothesis are based on the relative comfort of the alternative hand and arm movements when movement is unconstrained.

Purpose

The salient features coding hypothesis predicts that the response eccentricity and relative location effects on orthogonal SRC should not be restricted to unimanual responses but should also be obtained for bimanual keypresses. The end-state comfort hypothesis, in contrast, does not predict an effect for bimanual keypresses. It was developed to explain results obtained with unimanual responses and makes no clear prediction for bimanual responses because there is no unambiguous rotation axis for the response dimension in terms of end-state comfort. Consequently, if response eccentricity and relative location effects similar to those found with unimanual movement responses are obtained with bimanual keypress responses, then the salient features coding hypothesis receives additional support.

The response eccentricity effect for unimanual movement responses has been demonstrated in several experiments (Cho & Proctor, 2001; Michaels, 1989; Michaels & Schilder, 1991; Weeks et al., 1995). The standard finding is that a large up–right/down–left advantage is obtained when responding in the right hemispace, but this reverses to an up–left/down–right advantage in the left hemispace. Experiment 1 was designed to determine whether this same pattern of results occurs with bimanual left–right keypresses made with the index fingers of each hand.

According to the salient features coding hypothesis, the relative location effect on orthogonal SRC demonstrated by Weeks et al. (1995) for unimanual switch movements in their Experiment 2 should extend to bimanual keypress responses. Neither the original finding for unimanual responses nor the extension of this to bimanual keypresses is predicted by the end-state comfort hypothesis. In Experiment 2, one group of participants made keypress responses on a centred, active response box, and an inactive response box was placed to one side or the other in different trial blocks. Because only a single experiment exists in which the relative location effect has been shown for unimanual movement responses, another group of participants performed with unimanual left–right movement responses as a comparison. For this group, responses were made with a centred, active joystick, and an inactive joystick was placed to one side or the other in different trial blocks. This condition provides not only a replication of Weeks et al.'s (1995) study, but because a joystick rather than a toggle switch was used, the responses involved different muscle groups from those in Weeks et al.'s experiment. For both bimanual keypresses and unimanual joystick movements, the prediction was that the up–right/down–left advantage would be obtained when the active response device was located to the right of the inactive response device and that this advantage would decrease or reverse when the active response device was located to the left.

EXPERIMENT 1

Experiment 1 examined whether the response eccentricity effect on orthogonal SRC occurs when the responses are bimanual keypresses. The typical finding for unimanual movement responses is that the up–right/down–left advantage found at the body midline increases when responses are made in the right hemispace and reverses when they are made in the left hemispace (Michaels, 1989; Michaels & Schilder, 1991; Weeks et al., 1995). According to Lippa and Adam's (2001) end-state comfort hypothesis, the response eccentricity effect is due to the different hand postures adopted at different response locations. In a series of experiments we conducted recently (Cho & Proctor, in press-a), however, the response eccentricity effect was independent of whether the hand was in a prone or supine posture.

According to the salient features coding hypothesis, the response eccentricity effect is due to a change of relative salience at the different response locations. That is, when responses are made in the left hemispace, an up–left/down–right advantage occurs because the code for "left" is more salient than the code for "right", but when responses are made in the right hemispace, an up–right/down–left advantage occurs because the code for "right" is more salient. Thus, the salient features coding hypothesis predicts that the response eccentricity effect should occur regardless of the response mode. However, as noted earlier, the end-state comfort hypothesis provides no prediction about the response eccentricity effect with bimanual keypress responses.

The specific method used for Experiment 1 was modelled after that of Weeks et al.'s (1995) Experiment 1: The same stimuli were used, response location was manipulated between blocks of trials for each subject, the number of trials for each condition was the same, and so on. Other than the response mode, the main differences were that the intermediate ±15-cm response locations were excluded, and subjects participated in a single session rather than two sessions because there was no variable comparable to responding unimanually with the left or right hand, which was varied between sessions in Weeks et al.'s experiment.

Method

Participants

A total of 24 undergraduate students enrolled in Introductory Psychology at Purdue University participated in partial fulfilment of a course requirement. All were right-handed and had normal or corrected-to-normal visual acuity as determined by self-report.

Apparatus and stimuli

The experiment was controlled by software developed with the Micro Experimental Laboratory 2 (MEL 2.0) system. Stimuli were presented on the display screen of an IBM-compatible microcomputer, and viewing distance was approximately 60 cm. The display consisted of a fixation row of three purple asterisks (0.9 × 0.3 cm, 0.86° × 0.29°) and an imperative stimulus of three rows of three white asterisks (0.9 × 1.8 cm, approximately 0.86° × 1.72° of visual angle) that had the appearance of a rectangle. The imperative stimulus was presented above or below the fixation row, with a gap of 3.5 cm (3.34°) between the fixation row and the interior border of the stimulus.

Responses were made by pressing either one of two keys, the leftmost or rightmost response button on a MEL 2.0 response box, with the left and right index fingers. The distance between the two response keys was 6.7 cm, the distance between any two adjacent keys was 0.93 cm, and the size of each key was 1.0 cm × 1.0 cm. The responses were made with the box placed at three different locations: body midline and 30 cm to the left or right of the body midline.

Procedure

Participants aligned their body midline with the centre of the screen and placed their index fingers on the response keys. The experiment consisted of two 3-block sessions with a 2-min rest interval between them. Half of the participants performed the first session with the up–right/down–left mapping and the second session with the up–left/down–right mapping. The other half performed in the reverse order. Half of the participants began at the 30-cm position in the right hemispace and progressed to the left. The other half began at the 30-cm position in the left hemispace and progressed to the right. Participants performed 10 practice trials at the beginning of the each session. Each block was comprised of 50 trials, and a 30-s rest interval was given after completing each block.

At the beginning of each trial, the fixation point was presented in the centre of the screen for 500 ms. The imperative stimulus was presented either above or below the fixation point, both of which remained on until the participant responded. An incorrect response was followed by a 500-ms feedback tone. The fixation point for the next trial came on 1 s after the response when it was correct and after the feedback tone when the response was incorrect.

Results

RTs shorter than 125 ms and longer than 1250 ms (a total of 0.39 %) were removed from analysis as outliers. Mean RTs and percentages of error (PEs) were calculated for each participant. Analyses of variance (ANOVAs) were conducted on the mean RT and PE data, with mapping condition (up–right/down–left and up–left/down–right), response-box location (left, centre, and right), and response (left and right) as within-subject factors. The means of these data are shown in Table 1.

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

Response	*Mapping*	*Left location*		*Centre location*		*Right location*	
		RT	*PE*	*RT*	*PE*	*RT*	*PE*
Left	Up–left/down–right	307	1.50	310	2.67	322	2.67
	Up–right/down–left	319	3.71	303	3.16	295	1.50
	Mapping effect[b]	–12	–2.21	7	–0.49	27	1.17
Right	Up–left/down–right	287	2.67	288	3.33	318	4.20
	Up–right/down–left	317	2.35	291	1.33	290	1.51
	Mapping effect[b]	–30	0.32	–3	2.00	28	2.69

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

Reaction time. Mean RT was shorter at body midline ($M = 298$ ms) than at the right ($M = 306$ ms) or left ($M = 308$ ms) response-box location, but the effect of response-box location was not significant, $F(2, 46) = 2.99$, $p = .0604$, $MSE = 886$. The right response ($M = 298$ ms) was faster than the left response ($M = 309$ ms), $F(1, 23) = 21.33$, $p < .0001$, $MSE = 408$, and the main effect of mapping was nonsignificant, $F(1, 23) < 1$. The interaction of response and mapping was not significant, $F(1, 23) = 3.07$, $p = .093$, $MSE = 524$, although the left response showed a 7-ms up–right/down–left advantage and the right response a 2-ms up–left/down–right advantage.

Most importantly, the interaction between mapping and response location was significant, $F(2, 46) = 11.44$, $p < .0001$, $MSE = 1245$ (see Figure 1). An up–right/down–left advantage of 2 ms occurred at the body midline, and this advantage was amplified at the right response location (28 ms) and reversed at the left response location (–21 ms). Although the influence of

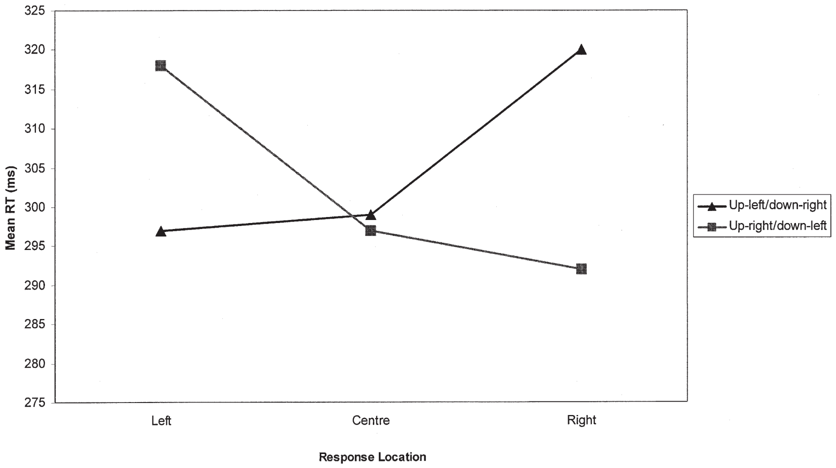

Figure 1. Mean reaction times for Experiment 1 as a function of S–R mapping and location of the response box.

response location on the mapping effect tended to be larger for the right response than for the left response (see Table 1), the three-way interaction of mapping and response location with response was not significant, $F(2, 46) = 1.99$, $p > .14$, $MSE = 293$.

Percentage error. Overall PE was 2.55%. Performance tended to be more accurate with the up–right/down–left mapping (2.26%) than with the up–left/down–right mapping (2.84%), but this difference was not significant, $F(1, 23) = 2.64$, $p = .1177$, $MSE = 9.23$. The other main effects were not significant, either, *F*s < 1. The interaction between the mapping and response was not significant, $F(1, 23) = 3.49$, $p = .0747$, $MSE = 24.63$, but there was a 0.51% up–left/down–right advantage with the left response and a 1.67% up–right/down–left advantage with the right response. This tendency is opposite that of the RT data. A way of describing the opposing relations is that responding tended to be slightly faster but less accurate when the stimulus occurred in the down position than when it occurred in the up position. This response bias does not create any problem for interpreting the comparisons of most interest—the mapping main effect and the interaction of mapping with response-box location—because they average across the up and down stimulus positions and the left and right responses.

PE showed the response eccentricity effect, $F(2, 46) = 4.15$, $p = .0220$, $MSE = 12.08$. At the body midline, performance was more accurate with the up–right/down–left mapping (2.25%) than with the up–left/down–right mapping (3.01%). At the right response location this difference was increased (1.50% and 3.44%), but at the left response location PE was less with the up–left/down–right mapping (2.09%) than with the up–right/down–left mapping (3.03%). This result is consistent with the RT data. No other interaction was significant.

Discussion

With bimanual keypress responses, the response eccentricity effect was found in the RT and PE data. The magnitude of the response eccentricity effect on SRC (49 ms) in this experiment was comparable to that in Weeks et al.'s (1995) Experiment 1 (50 ms and 48 ms for the left- and right-hand responses, respectively), on which the present experiment was modelled except for the use of bimanual keypresses compared to unimanual left–right switch closures. Like the experiments with unimanual responses, the up–right/down–left advantage increased at the right response location and reversed at the left response location. This result implies that the effect of response location is not due to the different hand postures across response locations, but to a change of the relative salience of the response alternatives.

EXPERIMENT 2

Given that the response eccentricity effect occurs with bimanual keypress responses, the next question is whether the effect of location relative to an inactive response apparatus also occurs. Experiment 2 was designed to answer this question. According to the salient features coding hypothesis, the orthogonal SRC effect is due to the relative salience of the code. Because the location code causing the orthogonal SRC effect is a central cognitive representation, the mapping effect has a similar basis for different response modes (Cho & Proctor, 2001; Weeks & Proctor, 1990). If the relative location of the response apparatus affects the salience of the response alternatives in accordance with the salient features coding hypothesis, then the orthogonal SRC effect should be affected by the location of the inactive response box. If the location at which responses are made is coded relative to the inactive response box, the up–right/down–left advantage should be evident when the inactive box is placed to the left side of the active response box but be reversed or disappear when it is placed to the right side of the active box. In contrast, the end-state comfort hypothesis provides no basis for expecting an effect of relative location.

In addition, a second group of subjects responded with unimanual aimed movements as in Weeks et al.'s (1995) Experiment 2, but with a joystick instead of a toggle switch. To manipulate the relative response location, an inactive joystick was placed to the left or right side of the active joystick, which was positioned at the body midline. This condition served two purposes. First, Weeks et al.'s experiment is the only one on record as showing this important effect of relative location. A replication generalizing the results to movements made with different muscle groups is therefore important. Second, this condition provided a control against which the effects obtained with bimanual keypresses could be compared.

Method

Participants

A total of 160 new undergraduate students from the same pool as those in Experiment 1 participated in partial fulfilment of a course requirement. All participants were right-handed and had normal or corrected-to-normal visual acuity as determined by self-report.

Apparatus and stimuli

The apparatus and stimuli were similar to those of Experiment 1, with the following exceptions. For subjects who responded with bimanual keypress, two MEL 2.0 response boxes (17 cm × 20 cm × 2.5 cm) were used, one as the active response apparatus and the other as the inactive response apparatus. The active response box was placed in line with the fixation point and stimulus set, and the inactive response box was placed to the left or right of the active response box, with the inner edge 6 cm away from the outer edge of the active box. For subjects who responded with unimanual aimed movements, responses were made by pushing the handle of an active joystick left or pulling it right with the right hand. Two joysticks (flight controllers for video games), one active and the other inactive, were placed on the table in front of the participants and fixed to the table with clamps. The active response joystick (CH Products Flight Stick) was placed in line with the stimulus position, and the inactive joystick (Thrustmaster Flight Control System Mark I) was placed with the inner side of the base 6 cm to the left or right of the base of the active response joystick. The active joystick was modified so that a response was measured in a discrete rather than continuous manner, and the joystick was connected to the first and fifth keys of the MEL 2.0 standard serial response box. The colour and shapes of the two joysticks were similar but not identical. The active joystick had an ivory-colour base (15.5 cm × 15.5 cm × 4.5 cm) and a black handle whose height was 14.5 cm. The inactive joystick's base (15.3 cm × 15.3 cm × 4.5 cm) and handle (its height was 16.5 cm) were both black. There were only two buttons on the handle of the active joystick, but five buttons on that of the inactive joystick. Thus, the joysticks were similar, but not identical, in appearance.

Procedure

Two groups of 80 participants were tested, one of which responded with bimanual keypresses and the other of which responded with joystick movements. The participants in both groups came from the same pool and had similar demographic characteristics, although they were not randomly assigned because the conditions were tested at different times of the semester. Participants in the keypress group aligned their body midline with the centre of the screen and placed their left index finger on the leftmost response button and right index finger on the rightmost response button of the active response box. They were instructed to press one of the two keys in response to the stimulus location. Participants in the joystick group aligned their body midline with the centre of the screen and grasped the handle of the active joystick with the right hand. They were instructed to move the joystick to the left or right in response to the stimulus location.

The experiment consisted of two 2-block sessions with a 2-min rest interval between them. Half of the participants performed the first session with the inactive response apparatus placed on the left side of the active response apparatus and the second session with the inactive response apparatus placed on the right side of the active response apparatus. The other half performed in the reverse order. After the first session was completed, participants left the experimental chamber, and the experimenter changed the placement of the inactive response apparatus during the rest interval. The location of the active response apparatus remained the same in two sessions. Each session was comprised of two mapping blocks with a 2-min rest interval between them. The order of the mapping conditions was counterbalanced across participants. Each participant performed 10 practice trials, and each block consisted of 50 trials. Trials were presented with the same timing as that in Experiment 1.

Results

A total of 0.41% and 0.26%, respectively, of the trials for the joystick and keypress groups were removed as outliers according to the exclusion criterion. Mean RTs and PEs were calculated for each participant as in Experiment 1. ANOVAs were conducted on the mean RT and PE data, with mapping condition (up–right/down–left and up–left/down–right), relative location of the active response apparatus (left and right), and response (left and right) as within-subject factors and response mode (keypress or joystick) as a between-subject factor. The mean values averaged across participants are shown in Table 2.

Reaction time. The response mode main effect was significant, $F(1, 158) = 233.36$, $p < .0001$, $MSE = 19{,}745$, with RT slower for joystick movements ($M = 440$ ms) than for keypresses ($M = 320$ ms). The slower RT with the joystick is due at least in part to the fact that the measure also included the time for the joystick to travel sufficiently far to close the switch. Mean RT did not differ overall as a function of the location of the inactive response apparatus, $F(1, 158) < 1$, $MSE = 2164$, being 381 ms when the active response apparatus was to the left of the inactive response apparatus and 379 ms when the active apparatus was to the right of the inactive one, and the main effect of response was not significant, $F(1, 158) = 1.57$, $MSE = 801$. However, response interacted with response mode, $F(1, 158) = 58.89$, $p = .0001$, $MSE = 801$. For keypress responses, the right response ($M = 315$ ms) was faster than the left response ($M = 325$ ms), but for joystick responses, the left response ($M = 433$ ms) was faster than the right response ($M = 447$ ms). This latter difference may be a consequence of it being easier to push the joystick left than to pull it right.

TABLE 2
Mean reaction time[a] and percentage of error in Experiment 2 as a function of mapping, relative location of the active response box, response, and response mode

			Left location		*Right location*	
Response mode	*Response*	*Mapping*	*RT*	*PE*	*RT*	*PE*
Joystick	Left	Up–left/down–right	437	1.51	441	0.99
		Up–right/down–left	433	1.58	421	1.65
		Mapping effect	4	–0.07	20	–0.66
	Right	Up–left/down–right	447	1.87	451	2.06
		Up–right/down–left	449	1.16	441	1.35
		Mapping effect	–2	0.71	10	0.71
Bimanual keypress	Left	Up–left/down–right	327	1.88	333	1.48
		Up–right/down–left	324	2.31	316	1.98
		Mapping effect	3	–0.43	17	–0.50
	Right	Up–left/down–right	309	2.10	317	2.36
		Up–right/down–left	319	1.26	315	1.40
		Mapping effect	–10	0.84	2	0.96

[a] In ms.

The mapping main effect was significant, $F(1, 158) = 4.98$, $p = .0271$, $MSE = 1836$, with responses faster for the up–right/down–left mapping ($M = 377$ ms) than for the up–left/down–right mapping ($M = 383$ ms). The interaction between mapping and response was also significant, $F(1, 158) = 22.47$, $p < .0001$, $MSE = 405$. The left response showed a 10-ms up–right/down–left advantage, whereas the right response showed no difference.

Most importantly, as in Weeks et al.'s (1995) Experiment 2, the interaction between mapping and relative location of the active response apparatus was significant, $F(1, 158) = 11.80$, $p = .0008$, $MSE = 1212$ (see Figure 2). A 12-ms up–right/down–left advantage was found when the active response apparatus was to the right of the inactive apparatus, whereas a 1-ms up–left/down–right advantage was found when the active response apparatus was to the left of the inactive one. No other interaction was significant, including the three-way interaction of these variables with response mode and the four-way interaction of those three variables with response, Fs < 1.0.

Percentage error. Overall PE was 1.68%. Although PE was lower with joystick responses (PE = 1.52%) than with keypress responses (PE = 1.85%), the main effect of response mode was not significant, $F(1, 158) = 2.97$, $p = .0866$, $MSE = 11.33$. Only two terms were significant. One was the interaction between mapping and response, $F(1, 158) = 34.91$, $p < .0001$, $MSE = 3.41$. The left response showed a 0.42% up–left/down–right advantage, whereas the right response showed a 0.80% up–right/down–left advantage. This pattern for the left and right responses was opposite that of the RT data and, as in Experiment 1, indicates slightly faster but less accurate responding to down stimuli than to up stimuli. Because this tradeoff did not involve position of the inactive response apparatus, it is not a factor in the relative location effect.

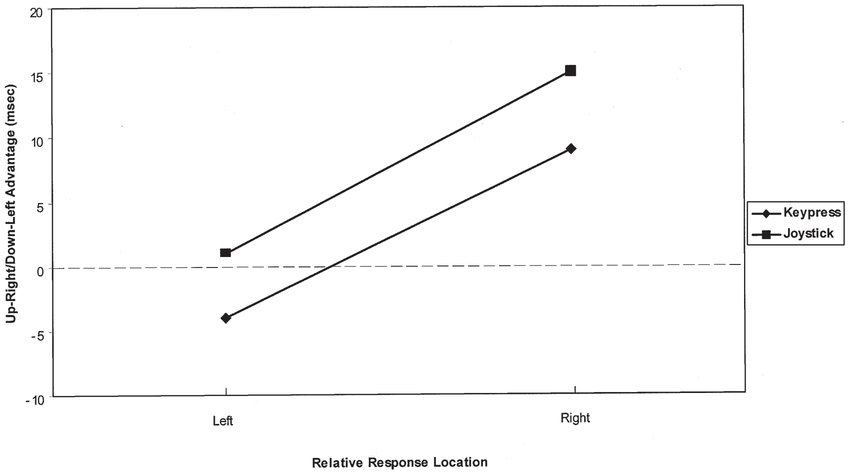

Figure 2. The up–right/down–left advantage for Experiment 2 as a function of S–R mapping and the relative location of the active response box.

The interaction of relative location and response was also significant, $F(1, 158) = 7.37$, $p = .0074$, $MSE = 2.62$. When the active response apparatus was located to the right of the inactive one, the left response was 0.26% more accurate than the right response; when the active response apparatus was located to the left of the inactive one, the right response was 0.22% more accurate than the left response.

Discussion

As in Weeks et al.'s (1995) Experiment 2, relative response location influenced the orthogonal SRC effect. With joystick responses, when the response location was right relative to the inactive joystick, an up–right/down–left advantage of 15 ms was obtained, but when the location was left, the mean up–right/down–left advantage was only 1 ms. Thus, although response location was held constant at the midline for all conditions, the location of the active joystick relative to the inactive one affected orthogonal SRC.

Relative response location also influenced the orthogonal SRC effect with bimanual keypress responses. When the location of the active response box was right relative to the inactive response box, an up–right/down–left advantage of 9.5 ms was obtained, but when the location of the box was left, the mean data favoured the up–left/down–right mapping by 3.5 ms. This relative location effect was small (13 ms), but of similar magnitude to that obtained with joystick responses (14 ms).

The results of this experiment, as well as those of Weeks et al.'s (1995) Experiment 2, confirm a strong prediction made by the salient features coding hypothesis but not by the other hypotheses proposed to explain orthogonal SRC effects. Specifically, the end-state comfort hypothesis does not predict an effect of location of an inactive response apparatus on orthogonal SRC because hand posture should be similar for the two relative-location conditions. Moreover, only the salient features coding hypothesis predicts that bimanual keypresses should yield similar results to those obtained with unimanual switch or joystick movements.

GENERAL DISCUSSION

In their recent article, Lippa and Adam (2001) noted, “Basically, two types of orthogonal SRC effects are known. On the one hand, there is an overall advantage of the up–right/down–left mapping. . . . On the other hand, there are S–R mapping preferences that vary with responding hand or with position of the response device” (p. 157). The salient features coding hypothesis, which emphasizes asymmetric coding in response selection, was developed initially to explain the first type of effect—that is, the up–right/down–left advantage that is obtained across a variety of stimulus and response sets. In contrast, the end-state comfort hypothesis (as well as its close relative, the ecological hypothesis), which emphasizes motor system factors, was developed to explain the second of the two types of orthogonal SRC effects, with a specific emphasis on the response eccentricity effect obtained with unimanual movement responses.

One approach to dealing with this state of affairs is to assume that the two types of orthogonal SRC effects have different causes and to explain them with fundamentally different mechanisms. Adam et al. (1998) and Lippa and Adam (2001) adopted this approach, with Adam et al. attributing the up–right/down–left advantage to asymmetric coding of the type suggested by the salient features coding hypothesis, only restricted to verbal codes, and Lippa and Adam attributing the response eccentricity effect to end-state comfort of the responding hand. An alternative approach is to attempt to develop an explanation that encompasses both types of orthogonal SRC effects. If such an explanation were possible, it would be superior in that it would provide a single, unifying account for the two types of orthogonal SRC effects. Weeks et al. (1995) adopted the second approach, as we have done in this article and in our other recent articles on the topic of orthogonal SRC, attempting to extend the salient features coding hypothesis to account for the response eccentricity effect. Note that although this hypothesis can in principle provide an account of both types of orthogonal SRC effects, the end-state comfort hypothesis is not capable of doing so because it has no means of accounting for the overall up–right/down–left advantage.

Response eccentricity

To explain the response eccentricity effect, Weeks et al. (1995) extended the salient features coding hypothesis with the plausible assumption that coding the location of the response apparatus as left or right increases the relative salience of the response alternative consistent with that coding. In other words, if the response apparatus is coded as left, the left response increases in salience relative to the right response, and the up–right/down–left advantage should be eliminated or reversed. Weeks et al. demonstrated in their Experiment 1 that the response eccentricity effect is a function of the location of the response apparatus and not the hand used for responding. That is, when the left and right hands were used at both ipsilateral and contralateral positions, response hand did not interact with the response-location variable.

Michaels and Schilder (1991) found an effect of prone versus supine hand posture on orthogonal SRC when unimanual switch-movement responses were made at body midline. With the prone posture, the left hand showed an up–right/down–left advantage and the right hand an up–left/down–right advantage. With the supine posture, these advantages were reversed. These results could be interpreted as suggesting that hand posture, and not just response location, may play a role in the response eccentricity effect. However, Cho and

Proctor (in press-a) showed that this effect of hand posture, as well as that of hand, does not interact with the response eccentricity effect, confirming that the eccentricity effect is primarily a function of response location, as the salient features coding hypothesis implies. Moreover, Cho and Proctor's results provided evidence that the hand posture effect itself is a consequence of relative location coding. A standard condition in which the response switch was held between the thumb and index finger was compared to one in which the switch was held between the ring and little fingers. For both prone and supine hand postures, the mapping preferences varied in a manner consistent with the hypothesis that the location of the response switch was coded with respect to the main part of the hand: The up–right/down–left advantage was larger when the switch was to the right of the main part of the hand than when it was to the left.

The end-state comfort hypothesis predicts a response eccentricity effect for unimanual movement responses but not for bimanual keypresses. In contrast, the salient features coding hypothesis predicts similar response eccentricity effects for keypresses because location of the response apparatus is the critical factor and not as a result of whether the response is being executed by a unimanual movement or discrete keypress. Experiment 1 of the present study supported this prediction of the salient features coding hypothesis, showing that bimanual keypresses yield a response eccentricity effect similar in direction and magnitude to that obtained with unimanual movement responses. Thus, as predicted by the hypothesis that location of the response apparatus affects the relative salience of the response alternatives, keypress responses made with different hands show response eccentricity effects similar to those shown by unimanual movement responses.

Relative position

The second piece of evidence reported by Weeks et al. (1995) was that in their Experiment 2 an effect similar to the response eccentricity effect occurred with a centred response switch as a function of its location relative to an inactive referent switch. The up–right/down–left advantage was evident when the location of the active switch was right relative to that of the inactive switch but not when it was left. This relative-location effect is particularly important because it cannot be explained by the end-state comfort hypothesis. Experiment 2 of the present study demonstrates that the relative-location effect is a robust phenomenon that can be obtained with unimanual movements of a joystick, which involve a different grip and different muscle groups from those of the switch movements used by Weeks et al. Thus, within the domain of unimanual movement responses for which the end-state comfort hypothesis was developed, this experiment confirms a key prediction of the salient features coding hypothesis that is not predicted on the basis of properties of the motor system.

Experiment 2 also verified an additional strong prediction of the salient features coding hypothesis, which is that an effect of location of the active response apparatus relative to that of an inactive apparatus should occur for keypress responses as it does for unimanual movement responses. An up–right/down–left advantage was evident when a centred response box was located to the right of the inactive response box, and this reversed to a small up–left/down–right advantage when the centred response box was to the left. This finding provides another illustration that the orthogonal SRC effects generalize across manual response modes, as implied by the salient features coding hypothesis but not by the end-state comfort hypothesis.

Implications of the salient features coding hypothesis

Numerous findings indicate that spatial information is represented in two different forms—coordinate and categorical spatial codes (Kosslyn, 1994)—and that spatial relations can also be coded verbally. The coordinate spatial representation specifies detailed information, such as precise distance, orientation, or size, whereas the categorical spatial codes and verbal codes explicitly specify qualitative spatial relations such as up, down, left, or right. Unlike coordinate spatial representations, both categorical spatial codes and verbal codes have an asymmetric property—that is, one object or feature is coded in relation to another. Thus, the up–right/down–left advantage should occur regardless of whether response selection is based on verbal or categorical spatial codes, as research suggests, except for situations in which response selection is based on coordinate spatial codes (see Cho & Proctor, in press-b, for a more detailed treatment of the issues discussed in this paragraph and the remainder of this section).

The general idea behind the salient features coding perspective is that stimulus–response translation is more efficient when a mapping maintains correspondence of the salience structure of the stimulus and response sets than when it does not. In the case of orthogonal SRC effects, the correspondence of the feature structure is maintained when up is mapped to right and down to left, allowing a simpler rule (make the response with the corresponding salience as the stimulus) to be applied than that for the reverse mapping (make the response that is the mirror-opposite salience of the stimulus). This account implies that both the salient and non-salient stimuli should tend to benefit from the up–right/down–left mapping, as found in the present study, because the same general translation rule is applicable to both.

The results of the present study are consistent with evidence from other studies that the direction and magnitude of the SRC effect for any particular situation is a consequence of multiple spatial codes. Spatial coding can occur with respect to a variety of different reference frames (Carlson-Radvansky & Irwin, 1993). Research has indicated that coding initially occurs automatically with respect to all of the available reference frames (Carlson, 1999). In choice reaction studies performance is probably based on the combined activation from the various reference frames. Studies of spatial correspondence effects (i.e., the Simon effect) when stimulus location is irrelevant support this view: When stimulus locations can be classified as left or right with respect to hemispace, hemifield, and relative location within a hemifield, each frame of reference contributes in an approximately additive manner to the Simon effect (Lamberts, Tavernier, & d'Ydewalle, 1992; Roswarski & Proctor, 1996).

Under conditions in which the stimulus display and response apparatus are positioned neutrally, up and right tend to be coded as more salient than down and left, producing the up–right/down–left advantage. When a face tilted 90° to the left or right is provided as a frame of reference, a spatial correspondence effect relative to the face is obtained in addition to the up–right/down–left advantage (Hommel & Lippa, 1995; Proctor & Pick, 1999). Likewise, when a frame of reference (e.g., an inactive response apparatus) is provided relative to which the response apparatus can be coded as left or right, this relative location coding of the position at which the responses are made causes the response consistent with the relative location code to be coded as more salient than the alternative response. Moreover, with unimanual movement responses, the factors of the hand used to respond, hand posture, and response eccentricity have approximately additive effects (Cho & Proctor, in press-a), implying that spatial codes relative to all available frames of reference contribute to performance.

A common finding across the experiments reported in this paper and those of Weeks et al. (1995) is that the response eccentricity effect is larger than the relative-location effect induced by an inactive response apparatus. The hypothesis that multiple spatial codes contribute to performance provides an explanation for this difference in effect sizes. The inactive response apparatus provides only a single frame of reference with respect to which the location of the active apparatus is coded as left or right, but when response eccentricity is varied, the response apparatus is coded as left or right relative to several frames of reference (e.g., body midline, the stimulus display, etc.).

The salient features coding hypothesis also implies that the orthogonal SRC effects should generalize across vocal responses. These were not used in the present experiments, but Cho and Proctor (2001) obtained an effect of initiating action on orthogonal SRC with keypresses that generalized to vocal responses as well. Their Experiment 1 showed that initiating a trial with a left or right keypress, thus emphasizing the side corresponding to the initiating action, affects the orthogonal SRC effect for keypress responses in a manner similar to response eccentricity. That is, an up–right/down–left advantage was evident only when the initiating action for a trial was a right keypress and not when it was a left keypress. Cho and Proctor's Experiment 2 showed that the same pattern of results occurred when the initiating action was the vocal word "left" or "right" and the task responses were also "left"–"right" vocalizations. Moreover, their Experiments 3 and 4 showed similar patterns of results when the initiating action was vocal and the task responses keypresses, or vice versa. These results imply not only that the orthogonal SRC effects have a similar basis for manual and vocal response sets, but that the effects are based in central processes for which an action in one response modality can affect response selection in another response modality.

Another implication of the salient features coding hypothesis is that the SRC effects that occur when left and right stimulus locations are mapped to up and down responses should also be explainable in terms of asymmetric coding. However, the relevant data are not as clear in this regard. It is unclear whether there is any overall right–up/down–left advantage corresponding to the overall up–right/down–left advantage found for a vertical stimulus dimension mapped to a horizontal response dimension (e.g., Lippa, 1996), as the salient features coding account implies. Response eccentricity has been found to affect the mapping preference for left–right stimuli mapped to up–down switch movements (Lippa & Adam, 2001; Michaels, 1989): A right–up/left–down advantage occurs when responding with the left hand in the left hemispace, and a right–down/left–up advantage when responding with the right hand in the right hemispace. However, the relations between locations that yield the advantage are the opposite of those when up–down stimuli are mapped to left–right responses. But, as Lippa and Adam note, the salient features coding hypothesis does not make specific predictions regarding these effects because the manipulation of response eccentricity is orthogonal to that of the orientation of the response set. Manipulations necessary to determine whether location of the response apparatus is crucial, as the salient features coding hypothesis implies, when left–right stimuli are mapped to up–down responses, or whether anatomical factors are most important, as the end-state comfort hypothesis implies, have yet to be conducted. Given the success of the salient features coding hypothesis in explaining the results obtained with up–right stimuli mapped to left–right responses, we think it likely that the hypothesis will ultimately be able to provide a satisfactory account for the SRC effects obtained when horizontally arrayed stimuli are mapped to vertically arrayed responses.

Conclusion

Lippa and Adam (2001) agree with us that "the salient-features coding principle accounts for the overall advantage of the up–right/down–left mapping across a range of stimulus and response sets (Weeks & Proctor, 1990; but see Adam et al., 1998), and for other phenomena (e.g., response precuing effects, Proctor & Reeve, 1986)" (p. 171). The point of disagreement is whether an account that ascribes a critical role to properties of the motor system, as does their end-state comfort hypothesis, is needed to supplement the salient features coding hypothesis in order to explain effects of response eccentricity, responding hand, and hand posture. The present experiments add to an increasingly large amount of evidence indicating that the effects of these seemingly motoric variables arise primarily from coding asymmetries. Their results, as well as those of Weeks et al. (1995) and Cho and Proctor (in press-a), are in much closer agreement with predictions derived from the salient features coding hypothesis based on the proposition that relative location coding systematically influences coding asymmetry than with predictions of the end-state comfort hypothesis. Thus, asymmetric coding of the type implied by the salient features coding hypothesis provides not only the most adequate account of the up–right/down–left advantage, but also the most adequate account of the response eccentricity effect and related results obtained with unimanual movement responses.

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Original manuscript received 31 July 2001
Accepted revision received 28 May 2002