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Stimulus and response representations underlying orthogonal stimulus–response compatibility effects

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One of the most important findings in recent years regarding response selection is that stimulus–response compatibility (SRC) effects occur for situations in which stimulus and response sets vary along orthogonal dimensions. For two-choice tasks, two types of orthogonal SRC effects are found: an overall advantage for the up-right/down-left mapping, and mapping preferences that vary as a function of position of the response apparatus and responding hand. We review evidence regarding the nature of both types of orthogonal SRC effects. Only asymmetric coding accounts have been proposed for the up-right/down-left advantage, and the evidence indicates that this asymmetry is a property of both verbal and spatial codes. Motoric and coding accounts, as well as a hybrid account based on end-state comfort, have been proposed for the second type of orthogonal SRC effect. In this case, the effects of response-apparatus position, hand, and hand posture conform more closely to predictions of the asymmetric coding accounts than to those of the motoric accounts. We also evaluate the mechanisms proposed by the alternative accounts in terms of related literature on the properties of spatial and verbal codes. Evidence indicates that spatial information is represented in categorical and coordinate codes, and both categorical spatial codes and verbal codes are asymmetric. Experiments on mental rotation suggest that it is unlikely that the direction of rotation is determined automatically by movement constraints, as the end-state comfort hypothesis suggests. An explanation in terms of salient features and referential coding can accommodate the range of orthogonal SRC effects.

Humans interact continually with natural and artificial environments. They process stimulus information, decide what actions to take on the basis of that information, execute those actions, and receive new stimulus information as a consequence. Because decision, or response-selection, processes play a central role in the continual interaction between perception and action, it is necessary to understand how these processes operate and what factors influence their duration and accuracy. Such understanding is important from a practical as well as a theoretical perspective, because a slow or incorrect decision can have disastrous consequences. For example, in January 1989, the pilots of a commercial aircraft shut down the functioning engine instead of the malfunctioning engine when a warning was received, causing the aircraft to crash and many people to die (Learmount & Norris, 1990). If this response-selection error had been prevented, the loss of aircraft and human life would not have occurred.

Response selection has been studied most extensively in choice-reaction tasks in which one of two or more responses to one of two or more possible stimuli is to be made upon the occurrence of a specific stimulus event. Response selection in such tasks is affected by many factors, including the number of stimulus–response (S–R) alternatives, the amount and type of practice that the subject has had, and whether the stimulus (and response) is a repetition of the immediately preceding one (see, e.g., Proctor & Dutta, 1995). Probably the most important variable affecting response selection is that of the mapping of stimuli to responses; the effects of such mapping are called S–R compatibility (SRC) effects. For tasks in which the stimulus and the response alternatives are spatial, performance is superior when the stimulus location corresponds to the response location than when it does not (see, e.g., Fitts & Deininger, 1954). For example, if subjects respond to left and right stimuli on a display screen by pressing left and right response keys, the compatible mapping of left stimulus to left response and right stimulus to right response typically yields better performance than the opposite, incompatible mapping does.

Spatial SRC effects of this type, in which the stimulus and response arrays vary along parallel dimensions (which we call parallel SRC effects), have been studied extensively because they reveal much about the relation between perception and action (Hommel & Prinz, 1997; Proctor & Reeve, 1990). The evidence strongly indicates that response selection in these cases is based on spatial stimulus and response codes, with reaction time (RT) being shorter when the stimulus code corresponds to the response code than when it does not (Hommel, 1997; Umiltà & Nicoletti, 1990). One finding that implicates use of spatial codes in response selection is that, when the limbs are crossed so that the left hand operates the right key

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and the right hand the left key, the SRC effect is independent of the slowing that results from crossing the limbs (see, e.g., Brebner, Shephard, & Cairney, 1972). Spatial coding can occur with respect to many frames of reference, and evidence suggests that the resulting SRC effects are a function of multiple codes (see, e.g., Hommel, 1994; Lamberts, Tavernier, & d'Ydewalle, 1992; Roswarski & Proctor, 1996). Most coding accounts assume that SRC effects are due in part to intentional translation of the stimulus information into a response code and in part to a tendency for a stimulus to activate its corresponding response automatically (Hommel, 1997; Kornblum, Hasbroucq, & Osman, 1990).

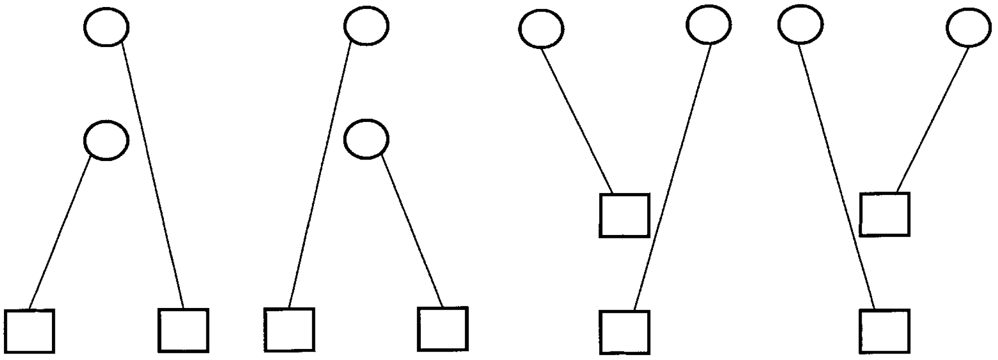
SRC effects also occur in situations in which the stimulus and response arrays are orthogonal (which we call orthogonal SRC effects; see Figure 1). Bauer and Miller (1982) reported the earliest demonstration of mapping preferences in choice RT experiments for orthogonal stimulus and response sets. In their Experiment 1, unimanual movement responses from a home key to an "up" or "down" key were made with the left or right index finger. The left hand showed a 116-msec RT advantage for the left-up/right-down mapping over the right-up/left-down mapping, but the right hand showed similar RTs for the two mappings. This difference between the two hands in mapping preference also appeared when the stimulus set was arrayed vertically and the response set horizontally. Up-right/down-left advantages of 65 and 21 msec were found when the subjects responded with the left and right hands, respectively.

The two findings illustrated in Bauer and Miller's (1982) experiments—an overall advantage for the up-right/down-left mapping and an effect of response variables such as left or right hand—have been replicated in numerous studies, leading Lippa and Adam (2001) to state:

> Basically, two sorts of orthogonal SRC effects are known. On the one hand, there is an overall advantage of the up-right/down-left mapping. Regardless of whether the response is manual or vocal, unimanual or bimanual, and whether the stimuli are spatial or symbolic, assigning up stimuli to right responses and bottom stimuli to left responses is easier than applying the reversed up-left/down-right 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)

These orthogonal SRC effects are of considerable theoretical importance because they occur for situations in which there is no spatial correspondence between stimuli and responses, and hence, no obvious coding basis for the effects (Bauer & Miller, 1982). Also, as Andre, Haskell, and Wickens (1991) noted, "Orthogonal S–R compatibility is an equally important issue from an applied design perspective" (p. 1546), because there are many situations in the design of home appliances, industrial equipment, aircraft cockpits, and so on, in which displays and controls are located orthogonally to each other.

The primary purpose of the present article is to review the findings regarding the two types of orthogonal SRC effects and to evaluate the explanations that have been proposed for each. In the first section, we review studies that have specifically examined orthogonal SRC effects, focusing in the first subsection on the up-right/down-left advantage and in the second on the orthogonal SRC effects for which factors associated with response position, hand, and hand posture play a role. We conclude that the up-right/down-left advantage is amenable to a coding explanation based on asymmetry of the codes along the respective dimensions, and that, although accounts based on properties of the motor system have predominated for the other type of orthogonal SRC effects, evidence suggests that they too can be explained in terms of S–R coding. In the second section, we consider findings from re-



a) Up-right/down-left mapping (Clockwise mapping)

b) Up-left/down-right mapping (Counter-clockwise mapping)

c) Right-down/left-up mapping (Clockwise mapping)

d) Right-up/left-down mapping (Counter-clockwise mapping)

Figure 1. The stimulus–response (S–R) arrangements for the various mappings in orthogonal S–R compatibility experiments. Circles designate stimulus locations, and squares designate response locations.

lated literature that bear on the nature of spatial representation. These findings are important for evaluating alternative accounts of orthogonal SRC effects, because these accounts differ in terms of the characteristics of the hypothesized spatial representations. Finally, in the concluding section, we will make the case that the evidence supports the view that orthogonal SRC effects are determined by multiple spatial codes, with the effects being produced by asymmetric coding of the alternatives along the stimulus and response dimensions and by alignment of reference frames.

ORTHOGONAL SRC EFFECTS

The Up-Right/Down-Left Advantage

Weeks and Proctor (1990) noted that Bauer and Miller's (1982) RT data for up and down stimuli mapped to unimanual left and right responses showed an advantage for the up-right/down-left mapping over the up-left/down-right mapping for both hands. They proposed that this advantage could be explained in terms of efficiency of coding-translation processes, in accordance with explanations applied to parallel SRC effects.

The Salient-Features-Coding Hypothesis

Weeks and Proctor (1990) explained the up-right/down-left advantage in terms of the salient-features-coding principle, used by Proctor and Reeve (1985, 1986) to account for a variety of SRC and precuing effects obtained in four-choice compatibility tasks. According to this principle, stimulus and response sets are coded in terms of their salient features, and the translation process is faster when salient features of the sets correspond than when they do not. The basic idea is that S–R translation is "based on rules derived from the structural relations between stimulus and response sets" (Proctor, Reeve, & Van Zandt, 1992, p. 736). Translation is faster when a simple rule based on correspondence of salient features can be applied than when one cannot be.

Weeks and Proctor (1990) hypothesized that the vertical stimulus dimension and the horizontal response dimension are coded asymmetrically, with the codes for right and up (or above) being more salient than those for left and down (or below; Chase & Clark, 1971; Farrell, 1979; Olson & Laxar, 1973). In accordance with the salient-features-coding principle, S–R translation is presumed to be faster when up is mapped to right and down to left than when the mapping is reversed, because the former mapping maintains the correspondence between the salience structure of the stimulus and response sets, whereas the latter does not. Thus, the rule relating stimuli and their assigned responses is simpler in the former case (*make the response with the salience corresponding to that of the stimulus*) than in the latter case (*make the response with the mirror-opposite salience of that of the stimulus*).[1]

An implication of this salient-features-coding hypothesis is that the up-right/down-left advantage should not be restricted to unimanual aimed-movement responses of the type examined by Bauer and Miller (1982), but should occur for a variety of spatially based responses. Weeks and Proctor (1990) demonstrated in their Experiment 2 that the up-right/down-left advantage occurred when the responses were keypresses made with the left and right index fingers. The advantage was evident not only when the hands were in a normal placement, but also when they were in a crossed placement, as found for parallel SRC effects (see, e.g., Brebner et al., 1972). In Weeks and Proctor's (1990) Experiment 3, a substantial up-right/down-left advantage was obtained when the responses were the spoken words "left" and "right." The fact that this advantage occurs with vocal responses strongly implies that it is based on cognitive rather than motor processes.

The salient-features-coding hypothesis also implies that the up-right/down-left advantage should occur for stimuli other than physical locations that convey location information and that, with left–right stimuli and up–down responses, performance should be better with the right-up/left-down mapping than with the alternative mapping. Proctor, Wang, and Vu (2002, Experiment 1) used all combinations of the location words "above" and "below" mapped to left–right keypresses in one condition and to "left"–"right" vocal responses in another. An up-right/down-left advantage was evident in the mean RT data in both cases, and the magnitude of this advantage was similar to that obtained when up–down physical locations were used as stimuli. The predicted right-up/left-down advantage has been found to occur for both left and right physical locations and left- and right-pointing arrows mapped to vocal "above"–"below" responses (Weeks & Proctor, 1990, Experiments 3 and 4). However, experiments with manual responses have tended to show an opposite, right-down/left-up advantage (Bauer & Miller, 1982; Lippa, 1996). Thus, although predictions based on asymmetric coding have been confirmed for the most part when up–down stimuli are mapped to left–right responses, the data obtained with left–right stimuli mapped to up–down responses are more ambiguous.

The Dual-Strategy Hypothesis

Umiltà (1991) also attributed the up-right/down-left advantage to asymmetric coding of the stimulus and response sets. However, he limited this asymmetry to verbal coding and proposed a dual-strategy hypothesis to explain the advantage. According to him, because the asymmetry originates from the verbal labeling stage, only verbal codes are asymmetric. Thus, when only spatial codes are processed, there should be no asymmetry in processing efficiency. The dual-strategy hypothesis assumes that the stimulus and response sets are coded both spatially and verbally. The verbal code, which has a polar referent, takes longer to form than the spatial code, which has no polar referent. For orthogonal S–R sets, if verbal codes are used in the translation process, then the up-right/down-left advantage occurs. If spatial codes are used, the up-right/down-left advantage does not occur.

Response properties and initiation of action. The dual-strategy hypothesis predicts that the up-right/down-left advantage should be larger when responses are slower than when they are faster because fast responding favors use of spatial codes, whereas slow responding favors verbal codes. Adam, Boon, Paas, and Umiltà (1998) varied the type of trial initiation in their Experiment 1, examining a subject-paced condition in which the subject initiated each trial by pressing the right response key, and a computer-paced condition in which each trial started automatically with a 750-msec intertrial interval (ITI). RT was shorter with computer-paced initiation than with subject-paced initiation, and, as predicted, the subject-paced condition showed the up-right/down-left advantage but the computer-paced condition did not. However, the results of Adam et al.'s Experiment 3 were inconsistent with the prediction that the up-right/down-left advantage would increase as RT slowed. Only computer-paced presentation was used in that experiment, but the ITI varied (750, 2,250, or 3,750 msec). Overall, RT increased with ITI, but there was no interaction of mapping with ITI, with a small up-right/down-left advantage of about 7 msec evident at all three ITIs.

Although there is little evidence that the up-right/down-left advantage increases as RT slows, Proctor and Cho (2001) found no significant up-right/down-left advantage when a 450-msec response deadline was imposed. In this case, the mean data showed only a 2-msec up-right/down-left advantage in both computer-paced (M = 293 msec) and subject-paced (M = 285 msec) conditions. Later, we will review evidence indicating that the elimination of the advantage with an extreme-speed emphasis likely reflects a shift from asymmetric categorical spatial codes, rather than from verbal codes, to reliance on coordinate spatial codes that are not asymmetric.

Adam et al. (1998) also found that when the RT distributions for the two mappings were divided into quantiles and the SRC effect was computed for each quantile, the size of the up-right/down-left advantage increased from the fastest to the slowest quantiles. They concluded that the increase of the effect size across RT quantiles reflects a switch of the codes used in the translation stage, from symmetric spatial codes to asymmetric verbal codes. However, the pattern of diverging functions obtained from the experiments with vertical stimuli and horizontal responses does not provide strong evidence indicating a switch from symmetric to asymmetric codes. This diverging pattern is also evident in experiments for which the stimulus and response sets are parallel (Roswarski & Proctor, 1996, Experiment 4; Vu & Proctor, 2002a), and the slope of the RT quantile plot is sensitive to factors other than the time course for two different processes (see, e.g., Vu & Proctor, 2002a; Zhang & Kornblum, 1997).

Umiltà (1991) pointed out that the up-right/down-left advantage was larger with vocal responses than with manual responses in Weeks and Proctor's (1990) study. According to Umiltà, vocal responses have a larger effect because they promote the use of verbal codes. Adam et al. (1998) examined the effect of response modality on the size of the up-right/down-left advantage in their Experiment 2. The advantage was evident in the subject-paced condition (12 msec) but not in the computer-paced condition (−3 msec), as was the case in their Experiment 1. However, there was no statistical difference between the two response modalities in the size of the up-right/down-left advantage (about 7 msec with vocal responses and 0 msec with manual responses). Moreover, for the subject-paced condition, in which the up-right/down-left advantage was evident, the effect sizes for vocal and manual responses were equivalent (10 and 12 msec, respectively). Cho and Proctor (2001) also obtained only 18- and 17-msec up-right/down-left advantages using the vocal response mode in their Experiments 2 and 4. On the other hand, in Lippa's (1996) and Lippa and Adam's (2001) experiments, 50–60-msec up-right/down-left and right-up/left-down advantages were found with unimanual aimed-movement responses. Dutta and Proctor (1992) also showed a 41-msec up-right/down-left advantage for bimanual keypresses. In sum, these results indicate that the magnitude of the mapping effect is not always larger with vocal responses than with manual responses, as would be expected on the basis of the dual-strategy hypothesis if the former promotes use of verbal codes.

Adam et al. (1998) concluded that with computer-paced presentation, it is possible to use a visually based S–R link, created on the previous trial, to select the response on the current trial, without using verbal codes. However, the visual S–R link is not available in the subject-paced condition because of the decay from longer ITI or interference of the initiating action. Thus, the initiating action promotes the use of the verbal codes, and the up-right/down-left advantage emerges only with subject-paced presentation. For this reason, the dual-strategy hypothesis suggests that the occurrence of the up-right/down-left advantage relies on whether or not each trial is initiated by an action. However, the up-right/down-left advantage has been obtained with computer-paced presentation in other studies. Proctor and Cho (2001) showed that the advantage was of similar magnitude when no initiating action was required and when trial initiation began with a right keypress. Furthermore, in Adam et al.'s Experiment 3, the up-right/down-left advantage appeared with computer-paced presentation. Originally, they assumed that the visual S–R link formed on the previous trial decayed as a function of time, but, as mentioned above, the effect of ITI on the up-right/down-left advantage did not occur, either. These results show no evidence that the S–R link established on the previous trial is used for selecting the response for the next trial.

Mapping-rule precues. The strongest evidence in support of the dual-strategy hypothesis reported by Adam et al. (1998) came from an experiment in which a precue that conveyed the appropriate mapping rule was presented at the beginning of each trial. The mapping rule was presented visually with either a verbal or a graphic description (with lines connecting an X in each stimulus location with a square in each response location). The dual-strategy hypothesis predicts that the up-right/down-left advantage should occur in the verbal-precue condition if describing the mapping rule verbally promotes the use of the verbal codes, but not in the visual-precue condition if describing the mapping rule graphically promotes the use of the spatial codes. Adam et al.'s results showed shorter mean RT in the graphic-presentation condition than in the verbal-presentation condition. More importantly, an up-right/down-left advantage of 52 msec was obtained when the mapping rule was presented verbally, but no advantage was evident when the mapping rule was presented graphically.

Kleinsorge (1999) obtained similar results. In his Experiment 1, the graphic precue consisted of two 90° sections of a circle, the arcs of which connected each possible stimulus location to the assigned response location, and the verbal precue consisted of a word and symbol string (e.g., down → left, up → right). As in Adam et al.'s (1998) study, mean RT was shorter with the graphic precue than with the verbal precue, and the up-right/down-left advantage was evident in the verbal-precue condition (52 msec) but not in the graphic-precue condition (2 msec). However, Kleinsorge noted that, in addition to the two precue conditions' differing in terms of the verbal/visual mode distinction, they also differed in whether the precued information could be processed sequentially or simultaneously. That is, the precue specified the two S–R mappings sequentially in the verbal-precue condition (i.e., the precue was read from left to right) but simultaneously in the graphic-precue condition. Note that this same distinction applies to the verbal and graphic precues used by Adam et al.

In Kleinsorge's (1999) Experiment 3, the precues were altered so that for both graphic and verbal presentation only one S–R pairing was specified explicitly. The other S–R pairing had to be inferred, meaning that it was generated after identification of the precued S–R pairing for both verbal and graphic precues. The dual-strategy hypothesis predicts that the up-right/down-left advantage should be more evident for the verbal-precue condition than for the graphic-precue condition. However, there was no significant difference between the two conditions in the magnitude of the up-right/down-left advantage. The dual-strategy hypothesis also predicts that the RT difference between the specified and unspecified responses should be greater with the graphic precue than with the verbal precue. This outcome is predicted because, with the verbal precue, both the specified and the unspecified responses can be based on verbal codes but with the graphic precue, the unspecified responses depend more heavily on the verbal code than the specified responses do. In contrast to this prediction, the up-right/down-left advantage was 30 msec for the specified responses and 18 msec for the unspecified responses with the verbal precue, but it was 13 and 14 msec, respectively, with the graphic precue. The results of Kleinsorge's Experiment 3 thus show that the difference in the up-right/down-left advantage resulting from the manipulation of verbal- and graphic-precue modes in both Adam et al.'s (1998) Experiment 4 and his Experiments 1 and 2 does not reflect a difference in the nature of verbal and spatial codes.

Why did the up-right/down-left advantage not occur when the complete mapping rule was presented in a graphic mode? Kleinsorge (1999) suggested that the answer to this question may lie in subjects' maintaining an image of the graphic precue. This image would likely be a coordinate spatial representation (i.e., one with continuous, metric relations), causing the imperative stimulus to be represented in a similar manner, rather than in a categorical spatial representation (i.e., one that codes the relative locations of objects; see the subsection Spatial Representations for a discussion of this distinction). Because the coordinate spatial representation would not have the property of asymmetry that a categorical spatial code would have, there would be no basis for a mapping preference. Reliance on coordinate spatial representations may have been encouraged by the fact that both Adam et al. (1998) and Kleinsorge used brief intervals (≤1.3 sec) between onset of the mapping rule and the imperative stimulus, and that Kleinsorge instructed subjects to maintain an image of the graphic precue.

Summary

The only viable accounts of the up-right/down-left advantage to date are the salient-features-coding and dual-strategy hypotheses, both of which attribute the advantage to asymmetric coding of the stimulus and response alternatives. For both accounts, the up-right/down-left mapping yields better performance because the salience relations in the stimulus set are maintained in the mapping to the response set. The major discrepancy between the two accounts is whether this asymmetry is a general property of coding or is restricted to verbal codes. The evidence directly concerning the up-right/down-left advantage points relatively strongly to the conclusion that asymmetry is a general coding property, as assumed by the salient-features-coding hypothesis. However, in keeping with the more general point of the dual-strategy hypothesis that response selection is not always based on asymmetric codes, under certain conditions (e.g., during extreme speed emphasis or when the complete mapping rule is presented graphically prior to the imperative stimulus), responding seems to be based on a spatial representation that does not have the property of asymmetry. Further evidence pertinent to this issue from related literature is presented in the later section, Characteristics of Spatial Representations and Orthogonal SRC.

Orthogonal SRC Effects That Vary With Responding Hand or Response Position

Although an overall up-right/down-left advantage is obtained in many circumstances, there is a second type of orthogonal SRC effects that varies as a function of anatomical factors and response position. The explanations that have been proposed for this type of effects can be classified within two categories: one in which the effects are attributed to the state of the motor system, and another in which they are attributed to cognitive coding.

Motor System Accounts

The movement-preference hypothesis. Bauer and Miller (1982) focused on the fact that the compatibility effects they obtained with unimanual responses at body midline varied in magnitude or direction as a function of whether the left or the right hand was used for responding. They assumed that movements are influenced by the context of prior and subsequent movements, and that this context determines movement difficulty. According to Bauer and Miller, subjects tend naturally to make a response in the direction of a stimulus. This tendency leads them to make an implicit movement, and the mapping rule required to make an appropriate response elicits an explicit movement, too. Implicit and explicit movements are combined together, and the combined movement produces a counterclockwise or clockwise movement. Because a clockwise movement can be executed more easily than a counterclockwise movement with the left hand, whereas a counterclockwise movement can be executed more easily than the other with the right hand, the left hand shows a preference for the left-up/right-down and up-right/down-left mapping, and the right hand shows the reversed preference. Thus, according to the movement-preference hypothesis, response hand determines the direction of the SRC effect.

However, there are both theoretical and empirical problems with Bauer and Miller's (1982) movement-preference hypothesis. Theoretically, the hypothesis is based on the assumption that subjects tend to respond in the direction of the stimulus. Simon (1969) originally suggested that there is a "basic natural tendency to respond toward the source of stimulation" (p. 174), primarily to explain why responses are faster when stimulus location corresponds to response location even when stimulus location is irrelevant to the task (a phenomenon known as the Simon effect). This assumed tendency implies that the important spatial variable for the stimulus is its location with respect to the observer. However, evidence indicates that spatial codes are formed in terms of relative stimulus location, and that these relative location codes, rather than stimulus location with respect to the observer, are of most importance to the Simon effect and to other spatial SRC effects (Lamberts et al., 1992; Roswarski & Proctor, 1996; Umiltà & Liotti, 1987; Umiltà & Nicoletti, 1985). For example, if both stimulus locations are in the right hemispace, RT will be faster if the left stimulus is mapped to the left response and the right stimulus to the right response, even though both are to the right of the observer. Thus, the evidence pertaining to spatial coding does not support the movement-preference account's central assumption that there is an initial tendency to respond in the direction of the stimulus.

Empirically, Michaels (1989) had subjects deflect a toggle switch left or right, using each hand at three response positions (on the midline, 30 cm ipsilateral, and 60 cm ipsilateral) and obtained results inconsistent with Bauer and Miller's (1982) movement-preference hypothesis. An up-right/down-left advantage was obtained with right-hand responses, whereas an up-left/down-right advantage was obtained with left-hand responses, these advantages being larger at the lateral response positions than at midline. The movement-preference hypothesis predicts the opposite relation and does not provide for response-eccentricity effects. In Michaels's second experiment, a horizontally arrayed visual stimulus set and a vertically arrayed response set were used. At body midline, a left-up/right-down advantage was obtained with the left hand, but no mapping preference was obtained with the right hand. However, at the ipsilateral response locations, the right hand showed a left-up/right-down advantage and the left hand showed no mapping preference.

The ecological hypothesis. Although Michaels's (1989) results showing that response eccentricity affected the preferred mapping were inconsistent with Bauer and Miller's (1982) movement-preference hypothesis, she 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). The major addition that Michaels made to Bauer and Miller's hypothesis was a proposal that the movement preferences were different at the lateral positions than at body midline, as reflected in her statement, "It 'feels' as if rotational preference would depend on the position of the hand and that responses solicited laterally (e.g., near arm's length) would reveal a clockwise preference for the right hand and an anticlockwise preference for the left hand" (p. 264). Michaels based her specific hypothesis, which we call the ecological hypothesis, on an ecological approach to SRC effects in general, according to which the preferred mappings are established by characteristics of the motor system (Michaels & Stins, 1997). The ecological approach assumes that the action system is linked closely with the perception system, and the state of the action system determines what response is most compatible. That is, motor system variables, such as which hand is used and the position at which it is placed, determine preferred mapping conditions. For this reason, the two hands show different movement preferences, and these preferences are influenced by the position of the responding hand.

Because hand position was confounded with hand posture in Michaels's (1989) study, Michaels and Schilder (1991) conducted experiments to evaluate the contribution of each to orthogonal SRC. Their Experiment 3 evaluated hand posture by having subjects perform by moving a toggle switch (apparently in an upright position), placed at body midline and grasped between the thumb and the forefinger, to the left or to the right, using a prone (palm down) or supine (palm up) hand posture.[2]

When responses were made with the left hand, an up-right/down-left advantage was obtained in the prone posture, but an up-left/down-right advantage was obtained in the supine posture. With the right hand, an up-right/down-left advantage was obtained in the supine posture, but no preference was obtained in the prone posture.

In Michaels and Schilder's (1991) Experiment 1, the effect of response eccentricity was examined with hand posture controlled. As in Michaels's (1989) Experiment 1, the stimulus locations were up and down, and unimanual responses were made at placements of 0, 30, and 60 cm relative to body midline. However, a constant hand posture was adopted at all positions: Subjects were instructed to grasp a block of wood to which a switch apparatus was attached, insert the index finger into the apparatus, and respond by deflecting the index finger to the left or to the right. The results were similar to those obtained by Michaels: Left-hand responses showed a large up-left/down-right advantage and right-hand responses showed a large up-right/down-left advantage at the ipsilateral 30- and 60-cm positions. Thus, the eccentricity effects reported by Michaels are not a function of the use of different hand postures at the different positions.

In both Michaels's (1989) and Michaels and Schilder's (1991) studies of response eccentricity, the hand used for responding was confounded with the position at which the response was made, because no contralateral positions were used. Weeks, Proctor, and Beyak (1995, Experiment 1) had subjects respond to a vertical stimulus array with unimanual left–right movements of a toggle switch at each of five locations: body midline, two locations to the right side, and two locations to the left side. An up-right/down-left advantage was found for the response locations to the right of midline and a reversed up-left/down-right advantage was found for the response locations to the left of midline, independently of the responding hand. Thus, contrary to the ecological hypothesis, the eccentricity effect is a function of neither hand posture nor the hand with which the responses are made.

Additional evidence that runs counter to the predictions of the ecological hypothesis is presented in the next section. In the section that follows it, we consider the end-state comfort hypothesis (Lippa & Adam, 2001), which attributes the second category of SRC effects to properties of the motor system, as does the ecological hypothesis, but in a coding framework that allows more specific predictions to be tested.

Coding Accounts

The salient-features-coding hypothesis. In their initial application of the salient-features-coding principle to orthogonal SRC effects, Weeks and Proctor (1990) explained the overall up-right/down-left advantage by testing predictions based on the assumption that up and right are the salient polar referents for their respective dimensions. They did not attempt to explain the changes in orthogonal SRC that occur as a function of hand, hand posture, and response position. Although Weeks and Proctor (1990) restricted their treatment to the up-right/down-left advantage, there is in principle no reason why the salient-features-coding hypothesis cannot be extended to account for the second type of orthogonal SRC effects. That is, salience is a relative property of stimuli and responses, not a fixed property, which implies that the salience of the alternatives can be affected by several factors (Reeve, Proctor, Weeks, & Dornier, 1992). This implication is consistent with views of salience developed from research on spatial interactions in perception (e.g., Brady, 1997), auditory space perception (Wightman & Kistler, 1997), and stimulus control in Pavlovian conditioning (Miller & Grace, 2003), and it has been supported in several choice-reaction studies, two of which we will describe. When a row of four equally spaced stimulus locations is mapped directly to a row of four response keys, operated by the index and middle fingers of each hand, performance benefits more if the two left or two right locations are precued than if the two inner or two outer locations are (Reeve & Proctor, 1984). Reeve et al. (1992) showed that this precuing benefit for the left–right locations can be enhanced or reversed by proximity manipulations that group the locations to increase the salience of the left–right or inner–outer distinction, respectively. Similarly, Vu and Proctor (2002b) showed that a phenomenon called the right–left prevalence effect (a stronger SRC effect for the horizontal dimension than for the vertical dimension when stimuli and responses vary along both dimensions simultaneously) can be reversed to a top–bottom prevalence effect if the vertical dimension is made more salient (e.g., by decreasing the discriminability of the stimulus locations along the horizontal dimension and using top–bottom effectors, an ipsilateral hand and foot, for responses).

Weeks et al. (1995) proposed that the eccentricity effects on orthogonal SRC demonstrated by Michaels (1989) and Michaels and Schilder (1991) for unimanual responses could be attributed to changes in relative salience. Specifically, they hypothesized that positioning the response apparatus to the left or right of midline increases the relative salience of the response corresponding to its placement (i.e., left becomes salient when the response apparatus is coded as left). A prediction of this hypothesis is that the orthogonal SRC effect should vary primarily as a function of the location of the response apparatus and not as a function of whether it is operated by the left or the right hand. Their Experiment 1, described earlier, in which response location and responding hand were varied factorially, showed only a significant influence of location on the orthogonal SRC effect, in agreement with the prediction.

Weeks et al.'s (1995) hypothesis makes a second prediction, which is that the mapping preference for a centered response location should be altered systematically by varying the relative position of the response device. If a referent object is present relative to which the device can be coded as left or right, effects similar to those observed when physical location varies should be evident. Weeks et al.'s Experiment 2 and Proctor and Cho's (in press) Experiment 2 confirmed this prediction for responses made with a toggle switch and a joystick, respectively. In both cases, the up-right/down-left advantage obtained when the response device was to the right of an inactive response device reversed to a nonsignificant up-left/down-right advantage when it was to the left of the inactive device. Confirmation of the predicted effect of an irrelevant response device provides particularly strong evidence that the mapping preference is a function of the relative salience of the response alternatives, because this effect is not predicted by explanations that rely on characteristics of the motor system.

Because the salient-features-coding hypothesis emphasizes response location, it does not provide an obvious explanation of the effect of hand posture on orthogonal SRC, reported by Michaels and Schilder (1991). We conducted an experiment similar to theirs in which subjects made unimanual movements of a switch, held between the thumb and the index finger, at body midline and at locations 30 cm to the left and right of midline (Cho & Proctor, in press). An overall advantage of 16 msec for the up-right/down-left mapping was obtained. Hand posture entered into a three-way interaction with mapping and response hand (see Figure 2), replicating the pattern reported by Michaels and Schilder: With the prone posture, the left hand showed 27 msec shorter RT for the up-right/down-left mapping than for the alternative mapping, and the right hand showed a −4 msec difference, but with the supine posture, this advantage reversed to −4 and 44-msec differences for the left and right hands, respectively. The mapping effect interacted with response location in a manner similar to that described above for Weeks et al.'s (1995) Experiment 1, but, most important, hand posture did not interact with mapping alone or with mapping and location. Thus, although hand posture affected performance, it had no significant influence on either the overall magnitude of the up-right/down-left advantage or on the differences associated with response eccentricity.

That the effect of hand posture on the up-right/down-left advantage is independent of the eccentricity effect and opposite for the right and left hands implies that the hand-posture effect is a consequence of the hand's providing a frame of reference. When the switch is grasped between the thumb and the index finger of the right hand, it is to the left of the main part of the hand when the hand is in the prone position, but to the right when the hand is in the supine position. Thus, relative to the hand, the switch is left with the prone posture and right with the supine posture. When the response is made with the left hand, this relation is reversed, and the switch is right with the prone posture and left with the supine posture. If location is coded with respect to multiple reference frames, as evidence discussed later indicates, then the code with respect to the hand should have an additive effect with the code developed with respect to response location.

Cho and Proctor (in press) obtained evidence supporting this relative location interpretation of the hand-posture effect. Subjects performed both while grasping the switch between the thumb and the index finger and while grasping it between the ring finger and the pinkie. For this latter grasping method, the location of the body of the hand relative to the switch is the opposite of that when the switch is grasped between the thumb and the index finger. With the thumb–index-finger grasp, responses at a midline location showed effects of hand posture on orthogonal SRC similar to those found by Michaels and Schilder (1991) and Cho and Proctor (in press, Experiment 1). Most importantly, the pattern of effects reversed with the ring-finger–small-finger grasp. In general, the results were such that the hand postures for which the

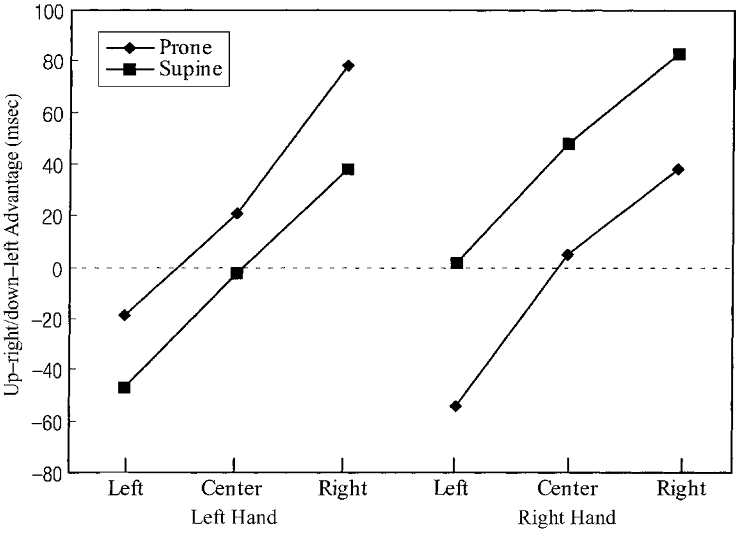


Figure 2. The up-right/down-left advantage as a function of switch location (left, center, right), hand (left, right), and hand posture (prone, supine) for reaction time in Cho and Proctor's (in press) Experiment 1.

switch would be coded as right relative to the hand yielded a large up-right/down-left advantage, whereas the hand postures for which it would be coded as left yielded a small up-right/down-left advantage.

Because the salient-features-coding hypothesis emphasizes relative location of the response apparatus as the crucial factor involved in the response-eccentricity effect, it predicts that similar effects of response eccentricity on orthogonal SRC should be obtained with keypress responses. We showed this to be the case for bimanual keypresses made with the index fingers of the left and right hands (Proctor & Cho, in press, Experiment 1). A large up-right/down-left advantage was obtained when the response keys were in the right hemispace, and this reversed to an up-left/down-right advantage when the keys were in the left hemispace. Moreover, an effect of relative location of the response apparatus similar to that obtained with unimanual movement responses was also found. When bimanual keypresses were made on the keys of a response box placed at midline, the orthogonal SRC effect was influenced by the location of an inactive response box. An up-right/down-left advantage was obtained when the location of the active box was right relative to the inactive box, and this advantage was eliminated when the location was left (Proctor & Cho, in press, Experiment 2). The fact that the response-eccentricity and relative-location effects generalize to bimanual keypress responses is very problematic for the motoric accounts of orthogonal SRC.

We recently obtained compelling evidence that the relative salience of the spatial response code is also affected by another manipulation that increases the prominence of one side relative to the other (Cho & Proctor, 2001). In Experiment 1, subjects made bimanual left–right keypresses to up–down stimuli. To initiate each trial, they pressed the right key in the right initiation condition and the left key in the left initiation condition. Because the response corresponding to the initiating action is more frequent and is stressed more than the other response, the salience of the response code corresponding to it should increase. If it does, the salient-features-coding hypothesis makes specific predictions about how the orthogonal SRC effect should vary as a function of the initiating action. Specifically, the up-right/down-left advantage should be reduced when the initiating action is left compared to when it is right, and this effect should occur regardless of whether the initiating actions and responses are keypresses or vocalizations. The up-right/down-left advantage was 26 msec in the right initiation condition but only 5 msec in the left initiation condition. A similar effect of initiating action was also found in Cho and Proctor's (2001) Experiment 2, in which the initiating action and task response were both vocal location words, "left" and "right": The up-right/down-left advantage was 27 msec with right initiation and 9 msec with left initiation.

The salient-features-coding hypothesis implies that this influence of the initiating action on the up-right/down-left advantage should be evident even when the action and task response are in different modalities. When the initiating action was a "left"–"right" vocal utterance and the response a left–right bimanual keypress (Cho & Proctor, 2001, Experiment 3), a 14-msec up-right/down-left advantage was evident in the right initiation condition, but no such advantage was observed in the left initiation condition. When the initiating action was a left–right keypress and the task response a "left"–"right" vocal utterance (Cho & Proctor, 2001, Experiment 4), the up-right/down-left advantage was 27 msec in the right initiation condition but only 7 msec in the left initiation condition. These results imply that the influence of the initiating action is not motoric in nature.

A strength of the salient-features-coding hypothesis in comparison with the others that have been proposed to explain the orthogonal SRC effects that vary as a function of response-related factors is that it can also explain the overall up-right/down-left advantage. Whereas motoric accounts are restricted to the effects obtained with unimanual responses and must be supplemented with other accounts for the effects obtained with keypresses and vocal responses, the salient-features-coding hypothesis does not suffer from such a restriction. The principal drawback of the hypothesis is the lack of a theoretical means of independently specifying relative salience in particular situations. However, this drawback is not insuperable. Predictions can be derived for a variety of situations in which empirical findings provide independent evidence of dimensional asymmetries (as in the case of Weeks & Proctor's, 1990, original tests of the salient-features-coding hypothesis), as well as when a plausible auxiliary assumption is made to explain a specific pattern of results (as in the case of Weeks et al.'s, 1995, explanation for response-eccentricity effects). To date, most tests based on the widely accepted fact that up and right tend to be the salient referents for the vertical and horizontal dimensions, respectively, as well as on the assumption that the relative salience of a response can be increased by variables that emphasize that location (either through the coding of the response apparatus or through the use of the response as an initiating action), have confirmed numerous predictions derived from the salient-features-coding hypothesis.

The referential-coding hypothesis. Lippa (1996) proposed what she called the "referential-coding hypothesis" to explain the orthogonal SRC effects obtained with unimanual movement responses. This hypothesis assumes that the orthogonal SRC effect is a spatial-correspondence effect much like that which occurs with parallel stimulus and response orientations. It is based on the fact that coding can occur with respect to various frames of reference (see Referential Spatial Codes, below). The basic idea is that, when possible, subjects will code the response dimension relative to an available frame of reference that allows that dimension to be represented parallel to the stimulus dimension.

According to Lippa (1996), when unimanual responses are made, response locations are coded spatially in reference to the intrinsic axis from fingertip to wrist to bring them in line with the stimulus locations. When subjects make unimanual up–down responses to stimuli in left or right locations, they typically hold the hand at a comfortable angle of about 45–90° relative to the line of the response keys (see Figure 3). This placement allows the up and down response locations to be coded as left or right relative to the hand. That is, when responses are made by the right hand, the down response can be coded as "left" and the up response as "right"; when responses are made by the left hand, the down response can be coded as "right" and the up response as "left." Similarly, when subjects make unimanual left–right responses to a vertically arrayed stimulus set, the comfortable hand posture allows response location to be coded as "up" and "down" relative to the intrinsic axis of the responding hand.

Lippa (1996) conducted five experiments to provide evidence for the referential-coding hypothesis. In Experiment 1, the stimuli were left–right locations, and the responses were up–down unimanual movements. As she predicted, the left hand showed an advantage for the left-up/right-down mapping, but the right hand showed an advantage for the left-down/right-up mapping. Her Experiment 4 obtained similar results for up–down stimuli mapped to left–right movements: The up-right/down-left mapping showed an advantage over the alternative mapping for the left hand, whereas the up-left/down-right mapping showed a smaller advantage for the right hand.

In Lippa's (1996) Experiment 2, subjects made unimanual up–down aimed-movement responses to a horizontal stimulus array, but held the responding hand in line with the vertical response array. In Experiment 5, the stimulus set was arrayed vertically and the response set horizontally, and subjects held the responding hand at a right angle to the line of the response array. In these experiments, in which the hand did not provide a frame of reference with respect to which the responses could be coded along a dimension parallel to the stimulus dimension, the preferred mapping did not vary with hand, as it did in Experiments 1 and 4, in which comfortable hand postures were adopted. There was no significant overall advantage for either mapping in Experiment 2 (left–right stimuli mapped to up–down responses), as was predicted by the referential-coding hypothesis, although both the mean RT and the error-rate data showed an advantage for the right-down/left-up mapping (approximately 25 msec and 2.5%, respectively). In Experiment 5 (up–down stimuli mapped to left–right responses), there was a significant overall 54-msec advantage for the up-right/down-left mapping.

In Lippa's (1996) Experiment 3, the response board was placed to the left or to the right of the subject's midline; with both placements, responses were made with the left or the right hand. In this situation, regardless of which hand is used, the angle with which the lower arm and hand are placed relative to the keys allows up to be coded as "right" and down as "left" when the board is in the left hemispace, and up to be coded as "left" and down as "right" when the board is in the right hemispace. The results showed large SRC effects of similar direction and magnitude for each hand, which varied primarily as a function of the response board location, rather than of hand.

The referential-coding hypothesis also seems to provide an explanation for puzzling effects obtained when compatibly assigned unimanual up–down responses are made to the up–down location of stimuli that also vary in whether they occur to the left or to the right side of the display. Cotton, Tzeng, and Hardyck (1977, Experiment 2; 1980, Experiment 1) reported two similar experiments that showed strong effects of the irrelevant left–right location variable that were dependent on

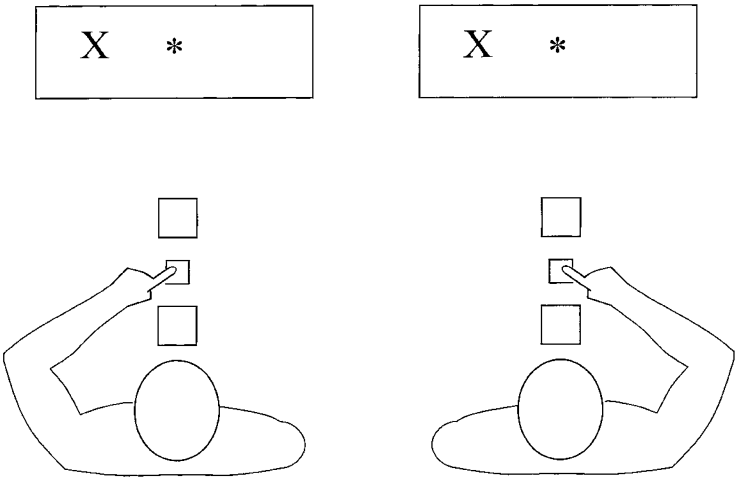


Figure 3. The postures of the left and right hands for the unimanual up–down response to the left–right stimulus set in Lippa's (1996) Experiment 1.

whether the left or the right hand was used for responding. With the left hand, responses were approximately 80 msec faster when the top stimulus occurred to the left and the bottom stimulus to the right than for the opposite pairings of locations. However, with the right hand, the reverse relation was obtained, with responses approximately 60 msec faster when the top stimulus occurred to the right and the bottom stimulus to the left than for the opposite location pairings. Assuming that the left hand is positioned so that the upper response is coded as "left" and the lower response as "right," and the right hand so that this coding relation is the opposite, the referential-coding hypothesis can account for this pattern of results.

Lippa and Adam (2001) noted that the results of Michaels and Schilder's (1991) Experiment 1, described previously, are problematic for the referential-coding hypothesis as applied to unimanual responses. In it, subjects responded by making a side-to-side movement of the index finger to up and down stimuli. This method of responding required that the hand be positioned at a right angle to the line with the horizontally arrayed response set, which should provide no frame of reference for coding the left–right responses as up or down. Yet, Michaels and Schilder obtained SRC effects that varied as a function of eccentricity similar to those obtained by Michaels (1989) when the hand position was not constrained in this manner.

A Hybrid Coding/Motor-System Account: The End-State Comfort Hypothesis

The fact that Michaels and Schilder (1991) obtained the response-eccentricity effect on orthogonal SRC when the hand was positioned at a right angle led Lippa and Adam (2001) to reject the referential-coding hypothesis in favor of a hybrid coding/motor-system account, the end-state comfort hypothesis. This hypothesis assumes that stimulus and response sets are processed as mental images, and that the imagined response keys or hands are mentally rotated clockwise or counterclockwise to align the response dimension with the stimulus dimension. Thus, as the referential-coding hypothesis suggests, orthogonal SRC effects are correspondence effects due to coding the response set along a dimension parallel to that of the stimulus set. A second assumption of the end-state comfort hypothesis is that the direction of the spatial transformation of the response dimension is automatically determined by constraints regarding real body movement, such as comfort in end-state posture. Consequently, the hypothesis is also a motor-system account that is a close relative of Michaels' (1989) ecological hypothesis. This point was made by Lippa and Adam, who stated, "The notion of an action-dependent interpretation of the S–R arrangement is not only held by the end-state comfort hypothesis, but also by the account of S–R compatibility proposed by Michaels and colleagues" (p. 172). Because the predictions derived from the end-state comfort hypothesis are based on a property of the motor system, end-state comfort, in the remainder of this article we include it as a member of the motor-system category of accounts.

According to the end-state comfort hypothesis, hand, hand posture, and response location affect the spatial transformation processes because they determine movement constraints. An inward movement is more efficient and is preferred by both the right and left hands when they are located at body midline or at ipsilateral locations (see, e.g., Bradshaw, Bradshaw, & Nettleton, 1990). To explain Weeks et al.'s (1995) finding that the mapping advantage is a function of response location rather than of hand for unimanual responses, Lippa and Adam (2001) proposed that when the hand is placed in the contralateral hemispace, the preferred movement is outward.

In Lippa and Adam's (2001) Experiments 1 and 2, subjects responded with the response plate placed to the ipsilateral side of the display. The experiments differed in whether the stimuli were oriented vertically and the response locations horizontally (Experiment 1), or vice versa (Experiment 2). The responding hand was held in a neutral position so that it did not provide a frame of reference that could be used to code the response set along a dimension parallel to that of the stimulus set. With vertical stimuli and horizontal responses (Experiment 1), the up-right/down-left mapping was preferred for the right hand and the up-left/down-right mapping for the left hand. With horizontal stimuli and vertical responses (Experiment 2), the left-up/right-down mapping was preferred for the right hand and the right-up/left-down mapping for the left hand. These results are consistent with predictions of the end-state comfort hypothesis.

Lippa and Adam's (2001) Experiment 3 provided the strongest evidence that the comfort in end-state posture of the hand determines the mapping preferences. In that experiment, subjects made unimanual up–down movement responses to the horizontally arrayed stimulus set, as in their Experiment 2, but the stimulus display was placed at a farther eccentricity than the response board was (see Figure 4). When the subject responded with the right hand, the response switch was placed on the right side of body midline and the stimulus panel was located to the right side of the response board. When the subject responded with the left hand, the response switch was placed on the left side of body midline and the stimulus panel was to the left side of the response board. A left-up/right-down advantage was obtained for the right hand and a right-up/left-down advantage for the left hand, as in their Experiment 2. This outcome indicates that the mapping preferences are a function of whether the responses are made with the left hand in the left hemispace or the right hand in the right hemispace, and they are not affected by the location of the stimulus panel.

Although end-state comfort is one factor that was consistent across the conditions of Lippa and Adam's (2001) Experiments 2 and 3, other factors were also consistent across the two experiments, including the locations of the response board and the hand positions. Therefore, the results cannot be attributed unambiguously to end-state

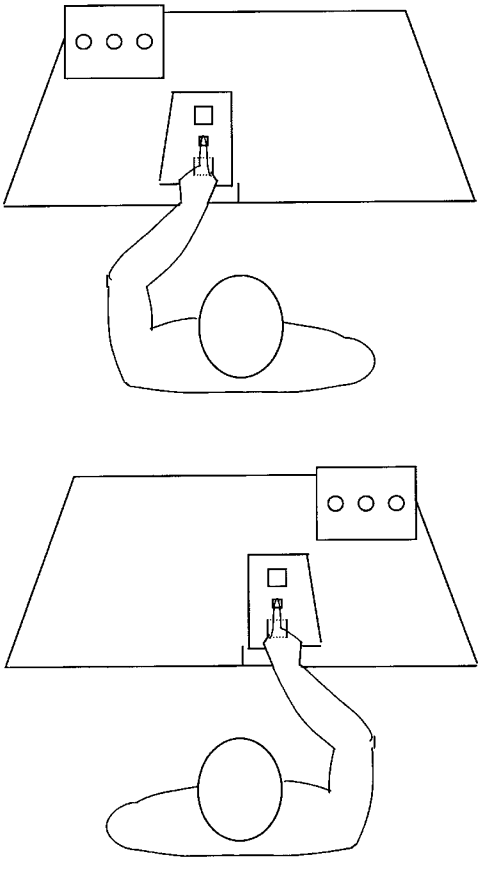


Figure 4. Stimulus and response arrangements for Lippa and Adam's (2001) Experiment 3.

comfort. Evidence that the location of the response board may be the crucial factor is apparent in a comparison of Lippa's (1996) Experiment 2 with Lippa and Adam's Experiments 2 and 3. They all called for a similar manner of responding (i.e., up–down responses with the hand in a neutral posture), but Lippa's experiment showed no interaction of mapping with hand. The major difference between her experiment and those of Lippa and Adam is that the response board was placed at a centered position in her experiment, rather than to the left or right side. Another plausible alternative explanation can be developed on the basis of the experiment of Cho and Proctor (in press), which showed that hand-posture effects are due to the hand's providing a frame of reference with respect to which alternative responses are coded. In Lippa and Adam's Experiments 2 and 3, the response hand was positioned with the index finger on the home key because the task required the subject to move that finger from the home key to the response key. With this hand posture, the hand covered the "down" response key and only the "up" key was visible (see Figure 4). With the left hand, the "up" key was right relative to the main part of the hand, whereas with the right hand, the "up" key was left relative to the main part of the hand. If the "up" key were coded as "right" and "left," respectively, in those two response conditions, and the "down" key were given the opposite code, the mapping effects would show the pattern obtained by Lippa and Adam.

Lippa and Adam's (2001) Experiment 4 demonstrated a direct effect of hand posture on orthogonal SRC. In that experiment, participants held a computer mouse attached at the front of a chinrest with the left or right hand, and made unimanual left–right keypresses to a vertically arrayed stimulus set with the index and middle fingers. The hand was held in one of two postures, in front of the subject with the back of the hand or the palm facing the subject, and the "left" and "right" keys were defined in terms of body midline. When the back of the hand faced the subject, there was an up-right/down-left advantage for the right hand and an up-left/down-right advantage for the left hand. However, when the palm was facing the subject, the effects reversed to an up-left/down-right advantage for the right hand and an up-right/down-left advantage for the left hand. Lippa and Adam proposed that this hand-posture effect occurred because the left hand prefers clockwise rotation and the right hand counterclockwise rotation when the back of the hand faces the subject, and these preferences reverse when the palm faces the subject.

However, there is a major problem with this interpretation of Lippa and Adam's (2001, Experiment 4) results. That problem is that the rotation preferences for the hands within the frontal plane do not seem to reverse direction when the mouse is held with the palm facing the person in comparison with when it is held with the back of the hand facing the person. With both hand postures, a clockwise rotation is more comfortable than a counterclockwise rotation for the left hand, and a counterclockwise rotation is more comfortable than a clockwise rotation for the right hand. Thus, contrary to Lippa and Adam's interpretation that the end-state comfort hypothesis predicts that the mapping effects will reverse for the two hand postures, it seems to predict that they should not. Lippa and Adam base the predicted reversal on rotation of the wrist about the sagittal plane that is orthogonal to the frontoparallel plane, but they provided no explanation as to why the critical rotation would be orthogonal to, rather than within, the plane along which the responses varied.

A final difficulty for the end-state comfort hypothesis is that it cannot explain the finding that placing an inactive switch to the left or to the right of the active response switch alters mapping preference. In Weeks et al.'s (1995) Experiment 2, responses were made at body midline with the right hand, and an inactive response switch was placed to the right or to the left of the active response switch. Because the location of the inactive switch should not alter the rotation preferences, the end-state comfort hypothesis predicts that the orthogonal SRC effect should not be affected by this manipulation. Yet, the up-right/down-left advantage was obtained when the inactive switch location was on the left, whereas a nonsignificant reverse advantage was obtained when the inactive switch location was on the right. That is, although response hand, response location, and hand posture remained the same across the conditions, the mapping effect was changed. Proctor and Cho (in press) recently demonstrated that this relative location effect, which is difficult to explain not only from the perspective of end-state comfort but also from any motoric perspective, is a reliable phenomenon, replicating it with joystick movements for which the hand grip and muscles controlling the left–right responses are different from those for switch movements.

Summary

Several authors have favored motor-system explanations of the second type of orthogonal SRC effects, because the effects vary as a function of the hand used to respond, the posture in which the hand is placed, and the location along the transverse plane at which the responses are made, all of which are variables that affect the state of the motor system. Alternatively, though, the effects of these response variables can be explained in terms of coding of the stimulus and response sets. When implications of motoric and coding accounts have been contrasted, the results have for the most part favored the coding accounts. According to the ecological hypothesis, hand position should be the crucial factor in the response-eccentricity effect, but the data show instead that, as implied by coding accounts, it is the location of the response apparatus, independent of hand, that is important. Although the end-state comfort hypothesis can account for this finding, it is unable to explain why location of a centered response apparatus relative to an inactive apparatus produces a qualitatively similar pattern of results. Moreover, results regarding hand and hand-posture effects on orthogonal SRC indicate that the critical factor is the frame of reference provided by the hand, and all of the results reported by Lippa and Adam (2001) in support of the end-state comfort hypothesis are subject to plausible alternative explanations.

An account based on the assumption that asymmetric coding of the type specified by the salient-features-coding hypothesis is the primary determinant of the orthogonal SRC effects, and that frames of reference are sometimes used to code the stimuli and responses along parallel dimensions, as assumed by the referential-coding hypothesis, seems capable of explaining the full range of results. Moreover, such an account has the virtue of explaining the orthogonal SRC effects that vary as a function of hand, hand posture, and response position in the same way that it explains the overall up-right/down-left advantage and the SRC effects for parallel S–R dimensions.

CHARACTERISTICS OF SPATIAL REPRESENTATIONS AND ORTHOGONAL SRC

In the previous two sections, we examined the ability of each of the hypotheses to explain the various findings obtained for orthogonal SRC tasks. These hypotheses also assume specific properties of visual information processing. Therefore, it is necessary to evaluate how well the assumed properties accord with those implied by results from other sources in the literature on spatial representation, verbal coding, coding asymmetry, referential coding, and mental rotation.

Spatial Representations

The salient-features-coding and dual-strategy hypotheses assume that the locations of stimuli and responses are coded spatially (Umiltà, 1991; Weeks & Proctor, 1991), and the end-state comfort hypothesis assumes the stimulus and response sets are represented as mental images. The salient-features-coding hypothesis assumes that the spatial codes for the stimulus and response alternatives are asymmetric, whereas the dual-strategy, referential-coding, and end-state comfort hypotheses assume no asymmetry in spatial coding. The properties of spatial representations have been examined in numerous studies, many of which suggest that there are both relational and analogue forms of spatial representation.

Spatial information is important for both recognizing objects and guiding actions, and each of these tasks seems to need different types of spatial information. In object recognition, each object can be represented as a combination of simple generalized primitive parts called *geons* (Biederman, 1987). According to Biederman, each geon represents a cone-type shape and is a viewpoint-invariant cue, and a particular arrangement of two or three geons specifies an object uniquely. All possible objects can be represented by the combination of the activated geons and their spatial relations. Hummel and Biederman (1992) portray these spatial relations as being coded explicitly, bound to the geons they describe, and invariant with viewpoint and geon identity. In other words, the capacity to recognize an object correctly from a variety of views "reflects the activation of a viewpoint-invariant structural description specifying the object's parts and the relations among them" (Hummel & Biederman, 1992, p. 480).

For other purposes, such as to control aimed movements, an analogue representation of spatial information is required and plays an essential role (Rosenbaum, 1991). Aimed movements are controlled by two mechanisms, feedforward and feedback controls. In feedforward control, spatial information is needed to program the required movement; for example, for preparing an aimed movement, information about the absolute, as well as relative, locations of objects and obstacles is required. In feedback control, quantitative spatial information about the difference between the actual and intended motions is needed to correct the error caused over time when a movement is being made.

In agreement with the need for both analogue and relational spatial information, Kosslyn (1994) has argued that there are two subsystems, *coordinate* and *categorical,* that code spatial information. The coordinate subsystem encodes a spatial representation that specifies metric spatial relations, such as precise distance, size, and orientation. The coordinate spatial representation is useful for guiding action, but it does not correspond to a particular movement. That is, it is a generalized type of representation. In contrast, the categorical subsystem encodes spatial codes that specify the relations among parts, such as left–right, up–down, and in front–back. Several characteristics define a categorical spatial code. First, a code specifies the general categorical relation between an object position and a referent position, not the precise metric information. Second, it defines equivalence classes. Thus, there is no intermediate value between any two relations. In addition, spatial codes developed by the categorical subsystem are determined by the task. These characteristics of categorical spatial codes are consistent with the fact that, in two-choice spatial SRC experiments, the stimulus and response locations are coded as up–down or left–right. In the remainder of this article, we often refer to coordinate spatial codes as "spatial representations" and categorical spatial codes as "spatial codes," for the sake of brevity.

Considerable evidence supports the distinction between the two spatial subsystems, some of which we describe here. Kosslyn et al. (1989) assumed that the left hemisphere is more effective than the right for tasks that require categorical spatial information, but the right hemisphere is more effective than the left for tasks that require coordinate spatial information. As predicted, the results with categorical spatial tasks have shown left hemisphere superiority, whereas those with coordinate spatial tasks have shown right hemisphere superiority (Hellige & Michimata, 1989; Kosslyn et al., 1989). Kosslyn et al.'s (1989) Experiment 2 illustrates this pattern. In it, plus and minus signs were presented at separations of 0.75 and 1.25 in. For the coordinate task, subjects judged whether or not the distance between two signs was greater than 1 in. For the categorical task, subjects judged whether the plus sign was left or right of the minus sign. Stimuli were presented briefly in the left or right visual field. RT was shorter for the coordinate task than for the categorical task. Most importantly, for the coordinate task, RT was shorter when stimuli were presented in the left visual field than when they were presented in the right, but for the categorical task, RT was shorter when stimuli were presented in the right visual field than when they were presented in the left.

Kosslyn et al. (1989) obtained evidence in their Experiment 3 that the type of spatial representation on which performance is based may change with practice. They had subjects judge whether a dot was above or below a short horizontal line (categorical task) and whether or not a dot was within a given distance from the line (coordinate task). The results showed right hemisphere superiority with the coordinate task and left hemisphere superiority with the categorical task, although RT was faster with the categorical task than with the coordinate task. However, the right hemisphere advantage for the coordinate task disappeared with practice, whereas the left hemisphere advantage for the categorical spatial task did not change. Kosslyn et al. (1989) speculated that, although the distance decision is performed by the coordinate spatial subsystem initially, it is performed by the categorical spatial subsystem after practice, because new spatial categories are developed.

Kosslyn, Chabris, Marsolek, and Koenig (1992) showed computationally that the coordinate spatial codes are likely produced by cells with large receptive fields, whereas the categorical spatial codes are produced by cells with small receptive fields. This hypothesis is supported by the results from a behavioral study conducted by Banich and Federmeier (1999). They demonstrated that in a categorical spatial task, responses were faster when the stimulus was presented in the central visual field than when the same stimulus was presented laterally in both left and right visual fields, whereas in a coordinate spatial task, the reverse response pattern was observed.

There is neurophysiological evidence that the two spatial subsystems are distinct (Banich & Federmeier, 1999; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Laeng, 1994). At least two visual pathways exist: a ventral system that projects to the inferior temporal cortex, and a dorsal system that projects to the posterior parietal region (Rossetti & Pisella, 2002). Much evidence suggests that the ventral system is primarily responsible for pattern recognition and perceptual experience, whereas the dorsal system is primarily involved in sensorimotor control (Bridgeman, 1999). Laeng (1994) showed a dissociation between categorical and coordinate spatial processing with unilateral stroke patients. When asked to examine whether a variant match figure was identical to a previously shown sample figure, the right hemisphere patients made more coordinate errors than categorical errors, whereas the left hemisphere patients made more categorical errors than coordinate errors. When the patients were asked which of the two variant figures was more similar to the previously shown sample figure, the same pattern emerged. The hemispheric difference was more evident with the parietal lesion group in both tests.

Numerous experimental results have been interpreted in terms of the distinction between the coordinate spatial representation associated with the dorsal pathway and the categorical spatial representation associated with the ventral pathway. Of relevance for present concerns is the fact that the contribution of the coordinate representation is largest when responses to visuospatial stimuli are made quickly. For example, Bridgeman (2000) noted that the Roelofs effect, a tendency to misperceive the position of the edge of a large pattern, is not evident in many subjects' responses when they make manual pointing responses immediately at stimulus offset. However, if responding is delayed, the Roelofs effect appears with the pointing responses. Perner and Clements (2000) noted that quick responding also is a factor in a related finding obtained with children 3 years old or younger.

When children are asked to choose in which of two locations a protagonist will look for an object when they did not witness an unexpected transfer from one location to the other, most will incorrectly select the current location of the object. A correct response occurs more often when the task requires pointing to the location, but only when the pointing response is made quickly. These and other results suggest that coordinate spatial codes are more of a factor when a task encourages fast responding to visuospatial stimulus information.

In summary, two kinds of spatial information are used for perceiving the external environment, guiding action, and engaging in other cognitive activities. The coordinate spatial representation contains detailed information and is useful for guiding action. This representation is general and does not link to a particular movement. Information about precise distance, orientation, or size is specified in the coordinate spatial representation. The categorical spatial representation specifies spatial information qualitatively. Because the categorical spatial codes assign a range of spatial information an equivalence class, they are relational representations that do not contain detailed information (Kosslyn, 1994). Although Kosslyn (1994; Kosslyn et al., 1992; Kosslyn et al., 1998) assumed that the spatial representations are output from a part of visual processes, it is unlikely that they are visual in nature. Auditory and tactile stimuli, as well as visual stimuli, can be represented spatially. Thus, spatial representation seems to be heteromodal or amodal (Landau & Jackendoff, 1993).

Verbal and Categorical Spatial Codes

Umiltà (1991) hypothesized that salience asymmetry emerges only in the verbal labeling process. Thus, the up-right/down-left advantage occurs only for situations in which verbal codes are formed for the spatial locations of the stimulus and the response. Adam et al. (1998) assumed that spatial codes are a "visualized spatial metric" (i.e., are analogue in nature), whereas verbal codes are a "verbalized spatial relation" (i.e., are propositional relations). However, as indicated above, spatial information is represented in two different forms, categorical (or relational) and coordinate (or analogue; Kosslyn, 1994). Thus, it is necessary to consider two different possible codes with an explicit relational format, verbal codes and categorical spatial codes.

According to Kosslyn (1994), categorical spatial codes and verbal codes both explicitly represent spatial relations, and the spatial codes relate to language closely. As described earlier, Kosslyn et al. (1989) showed that a categorical spatial task was performed faster when stimuli were initially presented to the left hemisphere, which is specialized for language processes, than when they were first presented to the right hemisphere, which is not. However, the verbal codes and spatial representations seem to have distinct functional properties. Spatial representations, especially categorical spatial codes, can be translated into verbal codes, but the categorical spatial codes do not seem to be a subset of verbal codes. Rather, the structure of the linguistically coded spatial relations seems to be similar to that of the categorical spatial codes (Landau & Jackendoff, 1993).

The distinction between spatial codes and verbal codes is demonstrated in cross-linguistic studies. Many verbal codes specifying a categorical spatial relation, such as *in*, *on*, and *off*, are prepositions in English. However, spatial prepositions do not directly link to the structure of spatial codes. The range of spatial relations specified by each preposition varies across languages (Bowerman, 1989). Rather, there are more categorical spatial codes than verbal codes that specify spatial relations. As was described earlier, Kosslyn et al. (1989) showed that a coordinate spatial task becomes a categorical spatial task with practice, implying acquisition of new categorical spatial codes. Verbal codes designating spatial location seem to select and combine certain spatial codes. Hayward and Tarr (1995) assumed that language about spatial relations adopts a preexisting categorical spatial structure. For this reason, there are structural similarities between spatial and verbal codes. Even though the categorical spatial codes for up–down and left–right have their own verbal description, one cannot say that these categorical spatial codes, unlike other prelexical categorical spatial codes, are a subset of verbal codes. Rather, the evidence suggests that there are distinct structures for the categorical spatial codes and for the verbal codes.

The categorical spatial system and the verbal system are closely linked to particular stimulus and response modalities. Spatial stimuli and keypress responses are more compatible with the spatial system than with the verbal system, whereas spatial words and verbal/vocal responses are more compatible with the verbal system than with the spatial system (Virzi & Egeth, 1985; Wang & Proctor, 1996). When subjects respond to the meaning or location of a spatial word with keypresses, the irrelevant location interferes with their ability to identify the word (the spatial Stroop effect), but an irrelevant word does not interfere with identification of the location (Lu & Proctor, 1994; Palef & Olson, 1975; Virzi & Egeth, 1985). However, with vocal responses, the spatial Stroop effect occurs when the location of the spatial word is relevant but not when its meaning is (Virzi & Egeth, 1985). In SRC proper, the magnitude of the SRC effect is greater when stimulus locations are paired with keypress responses, or spatial words with vocal responses, than when the pairings are reversed (Wang & Proctor, 1996).

According to Virzi and Egeth (1985), there are two separate systems, spatial and linguistic, that consist of independent stimulus analyzers, decision processors, and response stages. The spatial system processes spatial information, whereas the linguistic system processes linguistic information, and they produce spatial and verbal codes, respectively. The required response modality determines which system processes the information. With keypress responses, response selection occurs in the decision processor of the spatial system. Thus, RT is affected by the irrelevant location of a spatial word, which is processed by the spatial system, but not by the irrelevant meaning of a spatial word, which is processed by the linguistic system. With verbal responses, because response selection occurs in the linguistic system, performance is affected by the irrelevant meaning of a spatial word but not by the location in which the word occurs.

Although Virzi and Egeth (1985) assumed that these two systems are independent of each other except for a translation mechanism that operates prior to the decision stage, there seems to be a closer relation between the two systems. In their Experiment 2, vocal responses were affected by the irrelevant stimulus location (8 msec) and manual keypress responses were affected by the irrelevant stimulus meaning (8 msec). These results were replicated in other studies (Lu & Proctor, 2001; O'Leary & Barber, 1993). In Cho and Proctor's (2001) Experiments 3 and 4, the magnitude of the up-right/down-left advantage was affected by whether an initiating action was left or right, even though the modality of this action and that of the task response were different. That is, spatial codes are activated by spatial information from the perceptual and motor systems, and even from the linguistic system.

In sum, contrary to Adam et al.'s (1998) suggestion that spatial codes are visualized spatial metric information, they can also be a type of representation with an explicit relational format (Kosslyn, 1994). Categorical spatial codes and verbal codes for spatial relations are different from one another, even though they both explicitly encode spatial relations. The two kinds of codes are different outputs from different systems; the categorical spatial system and the verbal system, respectively. The categorical spatial system processes spatial information, such as the location of the stimulus, and is linked to the manual response system directly, whereas the verbal system processes word meaning and is linked to the verbal response system directly. However, these two systems are closely related to each other. In all kinds of SRC experiments, including SRC proper, the Simon effect, the spatial Stroop effect, and even the orthogonal SRC effect, SRC effects occur with different stimulus and response modalities (Adam et al., 1998; Cho & Proctor, 2001; Virzi & Egeth, 1985; Wang & Proctor, 1996; Weeks & Proctor, 1990).

Asymmetry of Salience

According to the dual-strategy hypothesis, salience asymmetry arises from verbal labeling and is restricted to verbal codes. In contrast, according to the salient-features-coding hypothesis, salience asymmetry extends to categorical spatial codes as well. Consequently, it is important to examine the evidence for salience asymmetry and to determine whether salience asymmetry is restricted to verbal codes.

The Vertical Dimension

Judgment of spatial location is usually faster with an "above" stimulus than with a "below" stimulus (Chase & Clark, 1971; Seymour, 1969). In Chase and Clark's Experiment 1, the word ABOVE or BELOW was presented in the center of a square, and a small circle was placed above or below the square. There were four kinds of stimulus displays: ABOVE-above, ABOVE-below, BELOW-above, and BELOW-below. Subjects indicated whether or not they thought the word meaning and the circle location matched by making one of two keypress responses. Verification time was 75 msec faster when the word was ABOVE than when it was BELOW and 85 msec faster when the circle was located above the square than below the square.

Seymour (1969) attributed the asymmetry of the spatial location judgment to scanning processes. According to him, the scanning process normally starts from the top location and proceeds downward. So, scanning is finished earlier when the stimulus word is ABOVE and the circle is above the square than when the stimulus word is BELOW and the circle is below the square. However, when an arrow pointing up or down was used instead of the word ABOVE or BELOW in Chase and Clark's (1971) Experiment 2, judgments were only 4 msec faster with the "up" arrow than with the "down" arrow and 7 msec faster when the circle was placed above the square than when it was placed below the square. According to Chase and Clark, the asymmetry obtained from the spatial verification task is not due to an invariant scanning process that proceeds from the top of the display to the bottom, but to the difference in processing time to compute each polarity for the vertical dimension.

Chase and Clark (1971) suggested that two factors contribute to the asymmetry of the positional judgment. First, adjectives pertaining to verticality presume the dimension of height, which is measured from a point of reference at the bottom. When an object is described as being ABOVE another object, the point of reference is also at the bottom; however, when an object is described as being BELOW another object, the point of reference is at the top. Consequently, the code for the relation BELOW needs one more step to be formed than does that for the relation ABOVE. Second, the spatial code for the up stimulus is formed faster than the spatial code for the down stimulus, because the upper position is normally attended first and the lower position is inferred afterward. The results obtained in Chase and Clark's Experiment 4 showed the advantage of the "up" spatial code over the "down" spatial code. In top-visible conditions, the circle was visible when it was above the square but masked when it was below the square, and in bottom-visible conditions this relation was reversed. When the circle was located below the square, there was no difference in RT between the top- and bottom-visible conditions. However, when the circle was located above the square, RT was faster in the top-visible condition than in the bottom-visible condition. This result shows the importance of the upper location and cannot be attributed to the characteristics of the verbal codes.

Clark and Chase (1974) assumed that the spatial code, which they called a picture code or perceptual code, is formed, and then the verbal descriptions about the spatial relation are constructed with the use of spatial codes to describe spatial relations or to verify descriptions against the spatial relation. Like Kosslyn (1994), they defined the spatial code as a representation that specifies the relation between an object and a referent. According to Clark and Chase, the spatial code "above" is formed automatically rather than the spatial code "below" in most situations, except when the observer decides to code the location of an object placed below the reference point or when the lower object seems to be more stable. When subjects were asked to describe two types of vertical configurations—symmetrical and asymmetrical—the word "above" was used more frequently than the word "below," especially to describe symmetrical spatial configurations (Clark & Chase, 1974, Experiment 1). If a verbal description about spatial relation is based on the activated spatial code, and the salient spatial codes are activated more frequently, it is possible to conclude that the spatial code "above" is more salient than the spatial code "below."

Clark (1973) proposed that the cognitive system required for understanding and expressing knowledge about spatial information consists of perceptual space and linguistic space, and the properties of both spaces are similar to each other. According to him, the reference points, lines, or planes, and the reference direction are needed to compute spatial information in perceptual space. All of the perceptual organs are placed symmetrically with respect to body midline. For this reason, perceptual space is symmetrical with respect to the sagittal plane. However, with the frontal and transverse planes, perceptual organs are asymmetrical. Because most of our perceptual organs, including eyes, ears, and nose, are located to the anterior side of the body, they are more sensitive to stimulation from the front of the body than from the back. In the transverse or horizontal plane, because the reference for the perceptual space is located at ground level, there is an asymmetry in the perceptual space. For these reasons, the forward and upward directions are treated as positive and the backward and downward directions as negative.

Clark (1973) suggested that linguistic space has the same properties as perceptual space, with three kinds of reference plane and the same positive and negative directions from them. The linguistic spatial terms, specifying the positive regions in reference to the frontal or transverse plane, are used as the basis for the scale name of each dimension. The structures of the verbal codes for the positive spatial terms are less complex than those for the negative spatial terms. They are called unmarked, whereas the negative spatial terms are called marked. Clark suggested that the positive spatial terms and codes for each dimension should be acquired before the negative spatial terms and comprehended faster. That is, the asymmetry of verticality, as well as that of other spatial terms, shown in the linguistic processes directly reflects the asymmetry of the perceptual space. Clark concluded that the spatial code for "up" or "above" is easier and faster to encode than the spatial code for "down" or "below" when it is involved in the comparison process.

However, it is difficult to separate the properties of the spatial codes from those of the verbal codes, because spatial codes have an explicit relational format and many have verbal terms that specify them. Sholl and Egeth (1981) tried to separate the properties of the spatial code from those of verbal labels. In their Experiment 1, they presented a display consisting of a circle, an uppercase N, E, S, or W placed at the center of the circle, and the numerals 1 and 2 placed to the left and to the right of the letter, or above and below it, in one of two rotation conditions, 0° and 90°. Subjects were asked to indicate the numeral located in the direction specified by the letter. In the 0°-rotation condition, the conventional frame of reference, in which north (N) is up, south (S) is down, and so on, is required to make a decision. However, in the 90°-rotation condition, subjects were instructed to use the map rotated 90° clockwise. Consequently, they had to respond to the N by selecting the numeral located on the right side of the centered letter N. Decision time was faster for the upper location than for the lower location. In the 0°-rotation condition, responding was 16 msec faster to N than to S; in the 90° clockwise rotation condition, responding was 25 msec faster to W ("west"), for which the to-be-identified digit was located on the upper side, than to E ("east"). Also responding was faster to the label N than to S regardless of the rotation condition. That is, the asymmetry of the verticality was obtained for both the spatial codes and the verbal codes. When subjects were instructed to use the map rotated 90° counterclockwise, responses were faster to the upper location and to the label N than to the lower location and the label S, respectively. The asymmetry in the vertical dimension was obtained with a clock-face context (Experiment 3) and with vocal "north"–"south" and "up"–"down" responses (Experiments 5 and 6).

Recently, Chambers, McBeath, Schiano, and Metz (1999) found the vertical asymmetry in a shape-comparison task. Subjects judged which of two comparison stimuli was more similar to a test stimulus. Comparison figures formed by combining a novel bottom half of a figure with the top half of the test figure were judged as more similar than those formed by combining a novel top half of a figure with the bottom half of the test figure. According to Chambers et al., because more meaningful and significant information would be obtained from the top of the object than from the bottom of the object, top is more salient than bottom.

In sum, although asymmetry has been studied and demonstrated in many studies using verbal material and on the basis of linguistic assumptions, such as markedness, the evidence does not support the conclusion that asymmetry in the vertical dimension is due to the verbal labeling process. The results obtained by Sholl and Egeth (1981) and Chambers et al. (1999) have indicated that, as Clark (1973) originally suggested, in the vertical dimension the upper region is more salient than the lower region, both perceptually and linguistically. Even though Sholl and Egeth did not directly show the salience asymmetry in the spatial codes “up” and “down” in their experiments, they demonstrated the importance of the “up” region in the perceptual space. If the salience of the codes is determined on the basis of perceptual importance, the spatial code for “up” or “above” should be more salient than that for “down” or “below.” That is, asymmetry in verticality is not only a property of the linguistic codes but also of the spatial codes, and it is possible to conclude that the spatial code “above” is more salient than the spatial code “below.”

The Horizontal Dimension

Asymmetry in the horizontal dimension is more complicated because it is difficult to find a perceptual or biological reason for it, unlike the asymmetry in the vertical dimension (Clark, 1973). Clark assumed that, because the perceptual organs were placed symmetrically with the reference of the sagittal frame, separating left and right is symmetrical. However, Olson and Laxar (1973) suggested that, as for “front–back” and “above–below,” there is asymmetry in processing the spatial terms “left”–“right” because most people have a dominant or preferred hand, most often the right. In their Experiment 1, they presented a stimulus display that, as did Chase and Clark’s (1971) display, consisted of a square, a small circle placed either to the right or to the left side of the square, and the spatial term LEFT or RIGHT placed at the center of the square. Right-handed subjects were asked to verify whether or not the meaning of the word and the location of the small circle correspond to each other by making keypress responses. RT was 94 msec shorter to the word RIGHT than to the word LEFT, regardless of circle location, suggesting that the verbal codes “left” and “right” are asymmetrical. Though the difference was not statistically significant ($p < .10$), responding was 47 msec faster to the circle placed to the right side of the square than to that placed to the left side of the square, regardless of word meaning, indicating that the spatial code “right” is formed faster than the spatial code “left.” For left-handed subjects, neither the meaning of the spatial word nor the circle location approached statistical significance, but the interaction of these variables with handedness was significant (Olson & Laxar, 1974).

The dependence of horizontal asymmetry on handedness was shown by another study. Làdavas (1988) replicated Olson and Laxar’s (1973, 1974) experiments and showed that the asymmetry in processing the horizontal spatial terms “left”–“right” was dependent on handedness, whereas the asymmetry in the vertical spatial terms “above”–“below” was not. Responses to the display containing the spatial term “above” were faster than those for “below,” regardless of handedness. However, right-handed individuals made faster responses to displays containing the word “right” than to those containing the word “left,” whereas left-handed individuals showed the opposite response pattern. Unfortunately, Làdavas (1988) did not analyze the location of the circle as an independent variable.

Although many studies have failed to show consistently the processing advantage of the spatial code “right” over the spatial code “left” (e.g., Farrell, 1979), Sholl and Egeth (1981) clearly showed that “right” was processed faster than “left” in their Experiment 3, in which spatial labeling was not required for the locational judgment task. As was mentioned earlier, they used a clock-face display as a stimulus. At the center of the clock face, one of the numerals 3, 6, 9, and 12 was presented. The letters *x* and *o* were placed to either side of the numeral, and the subjects were asked to name the letter located in the direction specified by the numeral in the clock-face context. In the horizontal dimension, directional judgment for the right location was 47 msec faster than it was for the left location. If the locus of the right advantage were the verbal labeling process, there should have been no right advantage in this experiment.

Farrell (1979) investigated the left–right confusion effect, which is defined as the fact that the discrimination of left–right is more difficult than that of up–down, by using the positional or directional judgment task with arrows and the letters U, D, L, and R. Contrary to the results of Sholl and Egeth’s (1981) Experiment 3, Farrell found only a small magnitude of right advantage. He concluded that, because the perceptual space was symmetrical in the horizontal dimension, neither the right or left spatial code nor right or left verbal code was more salient. Actually, although asymmetry was found consistently in the vertical dimension, it was not found in the horizontal dimension in Sholl and Egeth’s Experiments 1, 2, 6, and 7. However, as Olson and Laxar (1973, 1974) suggested, if asymmetry is dependent on handedness in the horizontal but not in the vertical dimension, the inconsistent asymmetry in the horizontal dimension revealed by the experiments investigating the left–right confusion effect can be explained. In fact, neither Farrell nor Sholl and Egeth controlled handedness in their experiments.

Làdavas (1987) found evidence that the up-right/down-left advantage obtained with bimanual keypresses depends on handedness. Subjects held a response cylinder in each hand and pressed a key located at the top of the cylinder to respond. The hands were positioned on a board level with a chinrest, with the left hand placed to the left side of the head and the right hand to the right side. The left–right responses were made to the onset of one of two LEDs located above and below fixation with either an up-right/down-left or an up-left/down-right mapping. Right-handed subjects responded 28 msec faster with the up-right/down-left mapping than with the other mapping, which is consistent with most orthogonal SRC studies. However, left-handed subjects responded 28 msec slower with the up-right/down-left mapping than with the other mapping, showing an up-left/down-right advantage instead of the typical up-right/down-left advantage. This dependence of the mapping advantage on handedness supports Olson and Laxar's (1973, 1974) idea that the asymmetry in the horizontal dimension arises from handedness, as well as Weeks and Proctor's (1990) idea that the direction of the orthogonal SRC effect is determined by the relative salience of each feature within dimensions.

Arrow Stimuli

Asymmetry did not occur in either the vertical or the horizontal dimension when, instead of a spatial word or letter specifying location, an arrow was used in matching experiments (Chase & Clark, 1971, Experiment 2; Olson & Laxar, 1973, Experiment 3; Sholl & Egeth, 1981, Experiment 4). One might interpret this finding as evidence that the locus of the asymmetry is the verbal labeling process. However, alternatively, the judgment could be processed without matching between the spatial codes for the location of the small circle and the direction of the arrow. Chase and Clark attributed the absence of asymmetry to the change from a matching task to a detection task. According to them, when an arrow was used, subjects were looking at the location to which the arrow pointed and judging whether or not the circle was there, rather than matching two codes to each other. Olson and Laxar (1973) also suggested that asymmetry occurs only when a comparison between two codes is required.

Just and Carpenter (1975) obtained evidence that arrows are coded asymmetrically and that the absence of asymmetry in the previous studies was a consequence of subjects' responding on the basis of global perceptual features arising from the configuration of the arrow and the circle. To prevent this possibility, they used upward- or downward-pointing arrowheads that were displayed to the left of a vowel or a consonant, one located above the other. The task was to judge whether the location of the vowel was the same as the direction of the arrowhead. This display format was intended to require explicit encoding of the direction in which the arrowhead pointed and in comparison with the encoded vowel. The results showed correct "yes" RTs (indicating that the arrowhead direction and vowel location matched) to be 76 msec shorter when the arrowhead pointed up than when it pointed down. Based on these and other findings, Just and Carpenter concluded, "The asymmetry between *above* and *below* (and *right* and *left*) is not specifically linguistic, but results from a more general asymmetrical conception of spatial dimensions" (p. 427).

Summary

Many researchers have suggested that the salience asymmetry in the vertical dimension is due to properties of perceptual space (e.g., Clark, 1973). Clark assumed that the properties of linguistic space reflect those of the perceptual space, and that, because the spatial code for "up" is simpler to compute and process than that for "down," the structure of the spatial term "up" or "above" is simpler than that of "down" or "below." There is a lot of evidence demonstrating this asymmetry in processing the location of the object in the vertical dimension (Chase & Clark, 1971; Sholl & Egeth, 1981). Thus, at least in the vertical dimension, the salience asymmetry is a property of both verbal and spatial codes. In the horizontal dimension, although evidence suggests that the left–right confusion effect is due to the verbal labeling process, one cannot say that the salience asymmetry comes only from the verbal labeling process. Overall, because asymmetry in the vertical dimension arises from perceptual and biological bias, it is an invariant property of the categorical spatial and verbal codes. However, because asymmetry in the horizontal dimension may arise from handedness, it is a variable property of the spatial and verbal codes.

Basically, the salient-features-coding hypothesis and the dual-strategy hypothesis use the same mechanism to explain the up-right/down-left advantage, with the exception that the latter restricts salience asymmetry to verbal codes. However, results obtained from experiments, in which the effect of labeling was separated from that of encoding, show that asymmetry is a property of both spatial and verbal codes (Olson & Laxar, 1973, 1974; Sholl & Egeth, 1981). It should be noted that Adam et al. (1998, Experiment 2) failed to demonstrate the dependence of the up-right/down-left advantage on verbal codes with the response-mode manipulation, which was intended to encourage subjects to use verbal or spatial codes.

Referential Spatial Codes

According to coding views, spatial information about stimulus and response locations is coded automatically. Response selection is slower when the S–R spatial codes do not correspond than when they do, in studies of both SRC proper and the Simon effect (Wallace, 1971). In orthogonal SRC experiments, response selection is faster when two salient polar referents are mapped to each other than when they are not (Weeks & Proctor, 1990). A categorical spatial code specifies a spatial relation between a target object and referent object(s) or location(s). For this reason, a stimulus can be coded spatially with respect to several referent points, such as the focus of attention, body midline, and other objects, and of all these spatial codes can affect the S–R translation processes (see, e.g., Lamberts et al., 1992; Roswarski & Proctor, 1996). Carlson-Radvansky and Irwin (1993) distinguished three kinds of frames by assigning spatial codes that differed in terms of referent point: viewer-, object-, and environment-centered frames.

Viewer-Centered Frames

Viewer-centered frames are based on the perceiver's perspectives and include retinocentric, head-centric, and body-centric frames. In the retinocentric frame, the point of fixation—that is, the region of the visual field that stimulates the fovea—plays a role as a reference point. Within this frame, a stimulus projected into the left hemifield is coded as left, and a stimulus projected into the right hemifield is coded as right. Spatial codes that occur in terms of a viewer-centered frame, excluding the retinocentric frame, are called egocentric spatial codes. The focus of attention (Umiltà & Liotti, 1987), location of hands, hand posture, and body midline belong to the category of egocentric frames that generate spatial codes. Any part of the body except the eye could be a reference point for spatial coding. For example, as indicated earlier, Lippa (1996) provided evidence that the intrinsic fingertip-to-wrist axis provides a reference frame when the orientations of the stimulus and response sets are orthogonal. Egocentric spatial codes are available at early stages of visual processing (Pouget, Fisher, & Sejnowski, 1999). The results from spatial choice–reaction tasks, including the Simon effect, SRC proper, and orthogonal SRC, suggest that the spatial codes eliciting the mapping effects are not formed in terms of the retinocentric frame. When the two possible stimulus locations were in one of two hemifields, mean RT was affected by irrelevant spatial information of an imperative stimulus (Umiltà & Liotti, 1987). That is, a Simon effect was obtained with respect to relative location, suggesting that the retinocentric frame is unimportant for the spatial mapping effect.

Umiltà and his colleagues stressed the importance of the spatial codes that are formed in terms of egocentric frames, especially the focus of attention. They assumed that the location on which attention focuses is a reference point for assigning spatial codes in experimental situations that yield the Simon effect (Nicoletti & Umiltà, 1989, 1994; Rubichi, Nicoletti, Iani, & Umiltà, 1997; Umiltà & Liotti, 1987). According to Stoffer (1991), the spatial code for irrelevant stimulus location is formed because of a covert shift of attention toward the stimulus position. If a stimulus is presented to the left or right side of the point on which attention is centered, a left or right spatial code is formed for the stimulus because the covert shift of attention is followed by the overt eye movement requiring spatial code. However, when stimulus displays are designed to require attentional zooming onto the stimulus, no spatial code is formed. Stoffer showed that the Simon effect did not occur when two possible stimulus locations are surrounded by a large rectangular precue. He interpreted this result as indicating that spatial codes were formed only when a lateralized attentional shift was required to refocus onto an imperative stimulus.

Object-Centered Frames

Spatial codes seem to be formed in terms of the stimulus's own intrinsic axis, too. This kind of reference frame is called an *object-centered frame*. If the stimulus is an object having its own intrinsic axis, the intrinsic axis provides a strong cue for assigning the stimulus into a spatial code. Bächtold, Baumüller, and Brugger (1998) showed that spatial codes were formed in the representation space by using ruler and clock images when the stimulus contained no spatial information. In their experiment, subjects were asked to imagine a 12-unit ruler or clock face and decide whether the number presented in the center of the screen with the ruler or the clock face was less than or greater than 6. The stimulus was a single number that ranged from 1 to 11, excluding 6. In one condition, subjects were instructed to respond to a number less than 6 with a left keypress and to a number greater than 6 with a right keypress; this mapping rule was reversed in the other condition. The results demonstrated that, when the context stimulus was a ruler, responses to a number less than 6 were faster with the left response key than with the right response key, whereas responses to larger numbers were faster with the right response key than with the left response key. However, when the context stimulus was a clock face, the response pattern was reversed. According to Bächtold et al., spatial codes were formed in terms of a representation space constructed by the context stimulus. In the ruler context, each number was aligned linearly in mental representation space. The numbers less than 6 were represented to the left of the number 6, and the other numbers were represented to the right of it. However, in the clock-face context, the numbers less than 6 were represented spatially at the right side, whereas the other numbers were represented at the left side. That is, the spatial codes are formed in reference to the representation of the context object.

Hommel and Lippa (1995) and Proctor and Pick (1999) showed that when stimuli were presented with respect to a face background, stimulus locations were coded in terms of an object-centered frame. In Hommel and Lippa's Experiment 1, subjects made left or right keypresses to stimuli in up or down locations that were presented in the context of a picture of Marilyn Monroe's face, tilted 90° to the left or to the right, so that the stimulus locations were the left and right eyes. Across the up-right/down-left and up-left/down-right mappings, mean RT was 7 msec shorter when the locations of the eye and the response key corresponded then when they did not. In Hommel and Lippa's Experiment 2, the eye–response key location-correspondence effect was also found when the context face was tilted 45°, the size of the effect decreasing as the degree of tilt was reduced. Proctor and Pick replicated Hommel and Lippa's results, obtaining a 17-msec effect of correspondence between eye and response key location in the context of Marilyn Monroe's face and smaller effects of the same type in the context of line drawings of faces. These results imply that the spatial codes can be formed in terms of an object's intrinsic axis.

However, spatial codes for stimulus location were formed not only in terms of the context face, but also in terms of other frames. In Hommel and Lippa's (1995) Experiment 1, the mapping variable, which contained the up-right/down-left and the up-left/down-right mapping conditions, did not reach statistical significance, but the 28-msec advantage for the up-right/down-left mapping was larger than the 7-msec eye–response key correspondence effect. Furthermore, when subjects were not allowed to move or tilt their heads by using a chin/forehead rest, a 42-msec up-right/down-left advantage was found (Proctor & Pick, 1999, Experiment 1B). Other experiments using a face context showed a tendency for the up-right/down-left advantage to occur, although it was not statistically significant in all cases. These results indicate that information for the stimulus locations is computed not only in terms of the object-centered frame, but also in terms of other frames automatically, such as egocentric and environmental frames.

Environment-Centered Frames

Spatial stimulus information can be processed in reference to an environment-centered frame. According to Carlson-Radvansky and Irwin (1993), "In an environment-centered frame, objects are represented with respect to salient features of the environment, such as gravity or prominent visual landmarks" (p. 224). For spatial SRC effects, coding of stimuli in terms of their locations relative to alternative stimuli and other displayed objects plays a crucial role. Lamberts et al. (1992) and Roswarski and Proctor (1996) manipulated the hemispace, the visual hemifield within the hemispace, and relative position within the hemifield independently, and showed that the Simon and spatial SRC effects occurred on the basis of all three frames. These results demonstrate that stimulus location is coded spatially with respect to the different reference frames. That is, the spatial codes in terms of the environmental frames, as well as those in terms of the other frames, can elicit the spatial mapping effect.

According to Hommel (1993), a spatial code is formed with respect to a referent object or frame, like a fixation point. In his Experiment 1, as in Stoffer's (1991) experiment, a large rectangle surrounding both possible stimulus locations was presented as a precue for 500 msec. Then, a red or green rectangle appeared as a target stimulus for 150 msec in one of two possible locations inside the precue frame. However, unlike in Stoffer's experiment, a noninformative reference stimulus, which was a gray rectangle, appeared between the two possible stimulus locations. Even though the lateralized attentional shift was not needed, a Simon effect was found in this experiment. Hommel (1993) concluded that spatial coding does not depend on the attentional shift or on other attentional operations. As Lamberts et al.'s (1992) experiments showed, spatial codes can be formed in terms of different reference points automatically.

Spatial codes for up and down are usually formed with reference to gravity (Carlson-Radvansky & Irwin, 1993; Garnham, 1989). In Carlson-Radvansky and Irwin's Experiment 1, four kinds of pictures were presented to subjects. The orientation of a reference object was normal in two conditions and was not normal, with the orientation of the reference object rotated to the right or left by 90°, in the other two conditions. The target object was egocentrically and environmentally above the object in one of the two normal conditions and was environmentally to the left or right of the reference object in the other normal condition. When the orientation of the reference object was not normal, a target object was located egocentrically and environmentally above the reference object in one condition and intrinsically above the reference object in the other condition. When subjects were asked to rate a sentence of the form, "The target object is above the reference object," the rating for the spatial term "above" in the reference of the egocentric/environment-centered frame was higher than it was in the reference of the object-centered frame. However, when pictures were presented to the subjects as they lay on their sides, so that the head was aligned with the top of the reference object depicted with abnormal orientation or with the bottom of the object in Experiment 4, subjects used the environment/object-centered frame more than the egocentric frame to assign a spatial term "above." Carlson-Radvansky and Irwin interpreted these results as indicating that the egocentric/environment-centered frame advantage obtained from Experiment 1 is a result of the environment-centered frame. In general, in a normal situation, the environment-centered frame seems to be dominant.

However, there was no evidence indicating that one frame of reference was always used for spatial coding in Carlson-Radvansky and Irwin's (1993) study, in agreement with other studies. Actually, in most situations, these frames for spatial assignment are confounded with each other, and all can be used for assignment. In spatial SRC experiments, all spatial codes activated by using any of the frames seem to cause mapping effects. Làdavas and Moscovitch (1984) showed that spatial codes for the stimulus and response locations could be formed both in the environment-centered and in the eye-centered frames of reference. However, although the spatial relation between anatomic hand and stimulus location can affect performance in spatial choice-reaction tasks (Klapp, Greim, Mendicino, & Koenig, 1979; Làdavas & Moscovitch, 1984), the effects of response location indicate the importance of the environment-centered frame for assigning spatial codes for left–right or above–below, as well as other spatial codes such as "connected with" or "between."

As was mentioned earlier, coding hypotheses assume that response locations are computed as spatial codes (see, e.g., Brebner et al., 1972; Wallace, 1971). The SRC and Simon effects are caused by the correspondence or noncorrespondence between stimulus and response spatial codes for response location, not response effector, such as hand. When both hands were placed on the same side of the body midline, an SRC effect occurred regardless of the position of the two hands relative to body midline (Nicoletti, Anzola, Luppino, Rizzolatti, & Umiltà, 1982). These results show that spatial codes for response location are formed in terms of the environment-centered frame, not an egocentric frame such as body midline. On the basis of parsimony of processing, it can be assumed that the spatial codes for response locations are formed by the same mechanism as those for stimulus locations (see Hommel, 1997). The fact that spatial codes for response locations are formed even though subjects do not specifically attend to the response locations in most experimental situations also shows the importance of the environment-centered frame.

The importance of referential spatial coding has been shown for orthogonal SRC, too. In Weeks et al.'s (1995) Experiment 2, the direction of orthogonal SRC was determined by the response switch location relative to an inactive response switch, even though the location of the active response switch was always at body midline. If the spatial codes for the response switch were formed with respect to an egocentric frame, the effect of the inactive response switch location on the orthogonal-mapping effect should have been absent. According to the salient-features-coding hypothesis, in the orthogonal SRC experiments, the spatial code for the response switch is important for determining the size or direction of the compatibility, because the location of the response switch increases the salience of the spatial code. This spatial code for the response switch seems to be formed in the environment-centered frame of reference.

Summary

Many spatial codes defined by the spatial relation between two or more objects are invariant even when their positions in terms of the egocentric or object-centered frames are changed, and seem to be used exclusively for understanding spatial information. Spatial codes for left, right, above, and below, like other spatial codes, also seem to be formed in terms of the environment-centered frame. However, the body midline, hand, or focus of attention can also play a role as a reference point, like other reference objects, to assign left–right or above–below spatial codes to stimulus locations. The experiments in which the up-right/down-left advantage was reversed when responses were made at the left side of body midline (e.g., Weeks et al., 1995, Experiment 1) show the flexibility of referential coding. When the salient reference object is absent, the body midline or focus of attention seems to provide a reference for spatial coding. However, it is unclear whether the spatial codes formed on the basis of different referents are available simultaneously with their relative impact determined by the task context, or whether the codes have a rank order, with a lower ranked spatial code formed only if a higher ranked spatial code is not available (see, e.g., Heister, Schroeder-Heister, & Ehrenstein, 1990).

Mental Rotation and Alignment of Stimulus and Response Sets

Unlike the salient-features-coding and dual-strategy hypotheses, Lippa and Adam's (2001) end-state comfort hypothesis suggests that the orthogonal SRC effect with unimanual keypresses is due to a rotational preference in spatial transformation processes that bring the imaged response set into alignment with the stimulus set. For example, when a stimulus set is arrayed vertically and a response set horizontally, the imaged response set is mentally rotated to the vertical dimension of the stimulus set to code the responses in parallel to the stimuli. Mental rotation has been studied widely since the initial work of Shepard and colleagues (e.g., Cooper & Shepard, 1975). The mental rotation process is based on mental images and consists of image-generation and -transformation processes. Unlike categorical representations, which consist of explicit symbols, the mental image contains visual analogue information. According to Kosslyn (1994), mental images are generated in the visual buffer, like other visual percepts. That is, visual perception and mental imagery share a common underlying mechanism, and mental images are formed with information from either visual perception or memory. To generate mental images from memory, the stored representations of an object's parts have to be combined with each other. Two kinds of spatial information, categorical spatial codes and coordinate spatial representations, are required to do so (Kosslyn, Maljkovic, Hamilton, Horwitz, & Thompson, 1995). To transform a mental image, transformation processes are needed. Kosslyn proposed two types of transformation, motion encoded and motion added. The motion-encoded transformation is the creation of a moving image as it activates a stored motion relation extracted during perception. The motion-added transformation involves the creation of image motion by alteration of the representation of an object's spatial properties and the imagery-mapping function.

Lippa and Adam (2001) assumed that the rotation of the response set is performed once when the subject's hands are placed into position for the task, with the direction of the rotation being automatically, and not strategically, determined by the constraints of real movement. They state,

> The coding of stimulus and response dimensions is fully determined by the relative posture of the hand. Once the hand is placed in a certain position relative to the response device and the body, there is only one interpretation of the setting, irrespective of whether it yields spatial correspondence or not. (p. 172)

As evidence for this view, Lippa and Adam cited the mental rotation studies of Sekiyama (1982) and Parsons (1987b), described below.

Sekiyama (1982) had subjects indicate whether a displayed line drawing was of a left hand or a right hand, by pressing a left or right response key. The hand could appear in any of eight orientations in 45° steps in the picture plane. RT was an increasing function of the amount of angular departure from upright, but the functions were asymmetric and mirror opposite for the left and right hands. When the stimulus was the right hand, mean RT was longest at 135° in the clockwise direction, but when it was the left hand, mean RT was longest at 225°. Sekiyama interpreted these results as suggesting that subjects form an initial hypothesis as to whether the presented hand is left or right and then rotate the mental representation of their own hand into congruence with the stimulus before responding. He attributed the asymmetry to mental rotation's being more efficient when it was in the preferred direction for actual movement of the hand than when it was not.

Parsons (1987b) replicated Sekiyama's (1982) results and showed that the decision time was longer when a stimulus hand was rotated inward than when it was rotated outward from the upright. This tendency was also found when subjects were asked to imagine moving the left or right hand to the orientation of the stimulus without left–right decision (Experiment 4). The left–right judgment time was closely correlated with the real movement time obtained from an experiment in which subjects were required to move their hand into the orientation depicted by the stimulus (Parsons, 1994, Experiment 1). Parsons (1994) concluded that subjects imagine moving their hand from its posture during the task to the orientation of the stimulus hand to compare the two, rather than imagine moving the stimulus hand to the orientation of their hand, because imagining moving their own hand is more familiar and easier than imagining moving the stimulus hand (see also Cooper & Shepard, 1975; Parsons, 1987a; Sekiyama, 1982).

According to Parsons (1987b), the spatial transformation in mental rotation is affected by kinematic properties of the real movement in some way. He suggested three plausible explanations for the effect of kinematic properties on the imagined spatial transformation. First, the rate of transformation may be slower when the orientation of the stimulus hand (and other body parts) is uncomfortable. The second possible explanation is that the initiation time to imagined spatial transformation may be longer for stimuli with awkward orientations. The third explanation is that imagined paths for awkward orientations may be longer. Parsons (1987b) concluded that the evidence supported the third explanation, with much of the effect of kinematic properties on the transformation process due to differences in lengths of the paths to move the imagined hand to the stimulus orientation. That is, when the orientation of the stimulus hand is not awkward or is within the limit of real movement, efficient paths to stimulus orientation can be used to transform the orientation of the hand in mental simulation. But when it is awkward or not within the limit, longer, inefficient paths are imagined.

It could be argued on the basis of neurophysiological evidence (see, e.g., Decety, 1996) that motor imagery is distinct from visual imagery and, consequently, that the studies above are not relevant to the transformations of the response sets hypothesized by Lippa and Adam (2001). However, Wohlschläger and Wohlschläger (1998) and Wexler, Kosslyn, and Berthoz (1998) obtained evidence that the processes involved in visual mental rotation overlap with those involved in manual rotation. In both studies, subjects were presented stimuli composed of rectangular parts, and they had to judge whether a figure was identical to a comparison figure except for rotation. When a manual rotation task had to be performed concurrently with the mental rotation task, a correspondence effect was obtained so that mental rotation was facilitated when it corresponded in direction to that of the manual rotation and was inhibited when it was in the opposite direction. Moreover, Wexler et al. found positive correlations between the speeds of rotation, as well as between the angles. The results of these two studies imply that motor processes are used even when abstract objects are mentally rotated.

However, there are several weak points in Lippa and Adam's (2001) end-state comfort hypothesis. First, all of the studies cited above, which suggest a role of motoric processes in mental rotation, were ones in which the tasks explicitly or implicitly required rotation of one object for comparison with another. This is not the case in the typical orthogonal SRC experiment, in which each of the two stimulus positions is assigned to a unique response. Second, in those studies, the evidence lies in mental rotation functions for which the time to respond on a particular trial is an increasing function of angular disparity. For orthogonal SRC, however, Lippa and Adam assume that the rotation occurs only once, when the hand is placed in position. The third weak point, which is related to the second, is that evidence indicates that mental rotation is strategic. For example, in comparing mental rotation with motion perception, Wohlschläger and Wohlschläger (1998) state, "Whereas motion perception is a rather automatic process, mental rotation is strategic" (p. 398). They go on to say that mental rotation "does not occur automatically" and "can be started and stopped voluntarily" (p. 398). In contrast, Lippa and Adam assumed that the rotation process in orthogonal SRC tasks is automatic. In sum, the process that is presumed by the end-state comfort hypothesis bears little resemblance to that evident in studies of mental rotation.

Although the results from the experiments requiring left–right body part judgments show the effect of real movement constraints on mental rotation (Cooper & Shepard, 1975; Parsons, 1987b, 1994; Sekiyama, 1982), they do not imply that the direction of mental rotation is automatically determined by the movement constraints. Parsons (1987b) concluded that the difference in time between awkward and nonawkward orientations of stimuli for left–right judgments is due to the difference in the length of the imagined paths, rather than to an inability to mentally rotate in the awkward direction. Thus, even though his and other results have indicated that the constraints of the real movement influence mental rotation performance, they provide evidence that subjects can mentally rotate an object in either direction and no evidence that the direction of the mental rotation is automatically determined by the constraints.

Although Lippa and Adam (2001) assumed that the mental rotation of the hand was performed only once per trial block, one might hypothesize that the rotation occurs on each individual trial. In this case, the mapping effect obtained in the unimanual orthogonal SRC experiments would be attributed to the difference, between inward and outward orientations, in the time taken to rotate the imagined response set to the stimulus orientation. However, this hypothesis does not seem plausible, either, because mental rotation is a complicated, slow process (Kosslyn, 1994). Usually, mean RT obtained from the left–right judgment experiments, or from experiments in which subjects were asked to imagine moving their hand without judgment, ranged from approximately 800 to 2,500 msec, including about 100–200 msec for rotating the imagined hand 90° (Cooper & Shepard, 1975; Parsons, 1987b, 1994; Sekiyama, 1982). The mean RTs obtained from experiments requiring mental rotation are much longer than those obtained by Lippa and Adam (2001), which were similar to those for aimed-movement responses when the S–R arrangement was parallel (see, e.g., Wang & Proctor, 1996, Experiment 3), and hence would not involve rotation. Thus, there is little evidence to suggest mental rotation on a trial-to-trial basis in the orthogonal SRC studies.

Summary

Evidence indicates that there are two types of spatial representations: a coordinate representation that specifies metric spatial relations and a categorical code that specifies the relations among objects. The categorical spatial codes are distinct from the verbal codes, and both types of codes show coding asymmetry. For the vertical dimension, up is more salient than down, and for the horizontal dimension, right is more salient than left, at least for right-handed persons. Thus, categorical spatial codes and verbal codes have the property of asymmetric coding assumed by the salient-features-coding hypothesis. The dual-strategy hypothesis, therefore, is incorrect in assuming that coding asymmetry is restricted to verbal codes, but is correct in the assumption that there is a type of spatial code on which responding can be based that is not asymmetric.

Spatial coding occurs on the basis of multiple frames of reference. Asymmetric coding along orthogonal dimensions occurs with respect to the various frames. If a frame of reference allows for the orthogonal stimuli and responses to be coded along parallel dimensions, referential coding of the type specified by Lippa (1996) occurs. Thus, the SRC effect that is observed in the mean RT data will be a weighted sum of the contributions of the compatibilities of the individual frames of reference. Moreover, the studies of mental rotation of limbs do not support the assumption of the end-state comfort hypothesis that the posture and position of the response hand automatically determine the direction of mental rotation. The results from the various studies of spatial representation are in close agreement with the coding properties specified by the salient-features-coding and referential-coding hypotheses. They are in less agreement with the coding properties specified by the dual-strategy hypothesis, which is the primary alternative for explaining the up-right/down-left advantage, and the end-state comfort hypothesis, which is the primary alternative for explaining the orthogonal SRC effects that vary as a function of anatomical factors.

CONCLUSION

Two types of orthogonal SRC effects are often obtained (Lippa & Adam, 2001). When stimuli vary along the vertical dimension and responses along the horizontal dimension, an advantage for the up-right/down-left mapping is found with various response modes. Also, with manual responses, the orthogonal SRC effect varies as a function of the eccentricity of the response apparatus, hand used for responding, and hand posture. Two categories of explanations have been proposed for these orthogonal SRC effects: those that attribute the effects solely to properties of cognitive coding, and those that attribute them to properties of the motor system.

Up-Right/Down-Left Mapping Advantage

Only coding accounts offer explanations of the overall up-right/down-left advantage. Two coding accounts have been developed to explain this advantage: the salient-features-coding hypothesis and the dual-strategy hypothesis. Both hypotheses attribute the up-right/down-left advantage to asymmetric coding of the stimuli and responses. They assume that response selection is faster when the more salient stimulus is mapped to the more salient response (and the less salient stimulus to the less salient response) than when the more salient stimulus is mapped to the less salient response (and vice versa). Thus, the only viable explanations of the up-right/down-left advantage that have been proposed to date attribute it to asymmetric coding.

The difference between the two coding accounts is that the dual-strategy hypothesis limits the asymmetric coding to verbal codes, whereas the salient-features-coding hypothesis does not. The evidence within the orthogonal SRC literature indicates that the up-right/down-left advantage occurs in a range of situations that extends well beyond those in which the dual-strategy hypothesis would predict an effect. Moreover, the evidence from the relevant literature on spatial and verbal coding indicates that asymmetric coding applies to categorical spatial codes as well as to verbal codes. Consequently, the most viable explanation of the up-right/down-left advantage is the salient-features-coding hypothesis.

Orthogonal SRC Effects That Vary With Responding Hand or Position of the Response Device

Both cognitive and motor-system accounts have been proposed for the type of orthogonal SRC effect that varies as a function of anatomical factors. Two coding accounts have been provided. The salient-features-coding hypothesis attributes the effects to coding asymmetry, as for the up-right/down-left advantage, the central idea being that variables that emphasize left or right increase the relative salience of the response corresponding to the emphasized location. The second coding account—the referential-coding hypothesis—attributes the effects to coding of the response dimension in parallel to that of the stimulus dimension on the basis of a frame of reference provided by the responding hand. The motor-system accounts, in contrast, attribute the effects to the state of the motor system. These accounts include the movement-preference hypothesis and the ecological hypothesis, as well as the end-state comfort hypothesis, which is a hybrid coding/motor-system account that derives its unique predictions from the motor system.

The most adequate account that attributes this type of orthogonal SRC effect to motor-system properties is the end-state comfort hypothesis. According to this hypothesis, the responses are mentally rotated into alignment with the orientation of the stimuli, with the direction of the mental rotation determined by constraints of real movement. This proposal is based on studies that show the rotation process to be affected by the constraints of real movement when a drawing of a body part is presented as a stimulus and subjects are asked to decide whether the stimulus is a left or a right body part (Cooper & Shepard, 1975; Parsons, 1987a, 1987b, 1994; Sekiyama, 1982). However, whereas the results of those studies illustrate voluntary rotation on a trial-to-trial basis, the end-state comfort hypothesis proposes that the direction of rotation is automatically determined by the constraints of the real movement, and that this rotation occurs only once for a set of trials when the hands are positioned to perform the task. Finally, the end-state comfort hypothesis cannot account for the effects due to location of the response switch relative to the position of a referent switch (Proctor & Cho, in press; Weeks et al., 1995).

The latter effects provide support for the salient-features-coding hypothesis, in that, when the response switch is coded as left, the salience of the left response is increased. The hypothesis can explain the additive effects of hand posture with those of response position, the hand apparently providing a frame of reference of its own relative to which the responses are coded. The salient-features-coding hypothesis is the only one that predicts that response eccentricity and relative position of the response apparatus will affect orthogonal SRC with bimanual keypress responses in a manner similar to unimanual movement responses, as we have found (Proctor & Cho, in press). Also, this hypothesis provides a straightforward interpretation of the effects of initiating the trials with a left or right action, and why these effects are also found with verbal stimuli and vocal responses, whereas the end-state comfort hypothesis does not.

Although the majority of results obtained for the second type of orthogonal SRC effect are in agreement with the salient-features-coding hypothesis and often run counter to predictions of the hypotheses that emphasize the motor system, there are some findings that are difficult to explain in terms of coding asymmetry. In particular, Lippa's (1996) demonstrations that the positioning of the responding hand affects orthogonal SRC do not seem to be explainable in terms of asymmetric coding. Specifically, several of her experiments show effects predicted on the assumption that, when possible, the hand is used as a frame of reference to align the response dimension with the stimulus dimension. These results are in agreement with the finding that a face can similarly provide a frame of reference with respect to which the stimulus alternatives are coded in parallel to the responses (see, e.g., Hommel & Lippa, 1995). Thus, the evidence suggests that, as the referential-coding hypothesis implies, orthogonal SRC effects reflect coding along parallel dimensions for situations in which frames of reference allow such coding to occur.

Orthogonal Choice Tasks With Three or More Alternatives

Relatively few studies have been conducted that examine performance of choice-reaction tasks with three or more alternatives when the stimulus and response sets are orthogonal. These studies provide little evidence that coding asymmetry plays a major role and suggest that frame alignment is the critical factor in enabling coding along parallel dimensions, as is specified by the referential-coding hypothesis. For a row of four stimulus locations mapped to a row of four response locations, precuing two of four locations in advance of the imperative stimulus typically yields a pattern of differential benefits in which precuing the two inner or two outer locations is most beneficial (Reeve & Proctor, 1984). This pattern of differential precuing benefits with respect to the row of response locations occurs when the four stimulus locations are oriented vertically (Proctor, Reeve, Weeks, Campbell, & Dornier, 1997), the primary effect of the orthogonal orientation being only to slow RT overall. Moreover, changes in the pattern of differential precuing benefits that occur with practice show transfer across changes in the orientation of the stimulus set (Proctor et al., 1997). These and other results suggest that the task is performed similarly with orthogonal arrays and with parallel arrays, except for an additional frame alignment transformation of the type proposed by the referential-coding hypothesis. In agreement with this implication, neither Biel and Carswell (1993) nor Lu and Proctor (1998) found a preference for a top-to-bottom or bottom-to-top ordered mapping of the stimuli to a left-to-right response-key order for five- and four-choice tasks, respectively.

Andre et al. (1991) reported results from three-choice tasks in which the stimuli were oriented vertically and the responses horizontally, or vice versa. In their tasks, responses were made with three fingers on a single hand, and the hand used for responding was varied. For both vertical stimuli mapped to horizontal responses and horizontal stimuli mapped to vertical responses, the mapping preference varied as a function of hand. With vertical stimuli and horizontal responses, the up-right/down-left mapping produced faster RTs than did the up-left/down-right mapping for the left hand, and this relation was reversed for the right hand. With horizontal stimuli and vertical responses, the left-up/right-down mapping yielded faster RTs than did the left-down/right-up mapping for the left hand, and this relation also was reversed for the right hand. Although the description of methods in Andre et al.'s study does not specify exactly how subjects positioned their hands, the entire set of results seems to be consistent with what would be expected if subjects were using the finger-to-wrist axis of the responding hand as a frame of reference for parallel coding, as the referential-coding hypothesis implies. Moreover, the results obtained for the vertical stimulus orientation appear to be opposite to the prediction of the end-state comfort hypothesis, because it is easier to turn the hands inward, which should lead to a preference for the up-left/down-right mapping with the left hand and for the up-right/down-left mapping with the right hand.

Reconciling Accounts of the Two Types of Orthogonal SRC Effects

Motor-system accounts in general, and the end-state comfort hypothesis in particular, are applicable only to the second type of orthogonal SRC effects—those that vary as a function of anatomical factors. These accounts have no mechanism for explaining the overall up-right/down-left advantage obtained with a variety of response modes. Consequently, acceptance of a motor-system account necessarily entails that this second type of orthogonal SRC effects will be explained in a different manner than the overall up-right/down-left advantage is (Lippa & Adam, 2001). Of the coding accounts, the referential-coding hypothesis and the dual-strategy hypothesis are also restricted in the types of orthogonal SRC effects they can explain. The referential-coding hypothesis is applicable only to the type of effects explained by the motor-system accounts, whereas the dual-strategy hypothesis is applicable only to the up-right/down-left advantage. One solution to this problem, which is the one proposed by Adam et al. (1998) and Lippa and Adam (2001), is to conclude that the two types of orthogonal SRC effects are fundamentally different phenomena that require different theoretical accounts.

A second solution to the problem is to try to develop a single account that encompasses both types of orthogonal SRC effects within a single framework. Given that the up-right/down-left advantage simply is not amenable to a motor-system account, this second solution necessarily implies that both types of effects are a consequence of cognitive coding. Another implication of this view is that coding asymmetry of the type specified by the salient-features-coding hypothesis must play a central role in the explanation because such asymmetry is strongly implied by the up-right/down-left advantage. An account of salient-features coding, coupled with referential coding of the type proposed by Lippa (1996), seems capable of explaining the broad range of findings regarding orthogonal SRC. In other words, the evidence suggests that the effects are due to the way in which the orthogonal stimulus and response sets are coded. The two alternatives for each tend to be coded asymmetrically, with response selection benefiting from correspondence of the asymmetry relations for the stimuli and their assigned responses. In addition, when a frame of reference allows one dimension to be coded in parallel to the other, response selection benefits from a correspondence of the parallel code mappings.

The research on categorical spatial codes suggests that they can be formed in terms of different types of reference frames, including retinocentric, ego-centered, and object-centered frames. Several results suggest that the observed orthogonal SRC effect in any specific situation reflects the additive effects of multiple spatial codes. For example, although placing an inactive response apparatus to the left or right of a centered active response apparatus influences orthogonal SRC in the manner predicted on the basis of relative location coding, the effect is smaller in magnitude than that produced by varying the eccentricity of the response apparatus. A likely reason for this is that, when the response apparatus is placed to the right of the subject, it is coded as "right" relative to several frames of reference. In contrast, when the response apparatus is centered at midline and another one is located to the left, the only referent with respect to which the response apparatus is coded as "right" is the inactive apparatus. As another example, the independent effects of hand posture and response eccentricity imply that the coding of the response alternatives relative to the hand is distinct from the coding of the alternatives relative to the response apparatus (Cho & Proctor, 2002). As a final example, in studies providing evidence for coding of the stimulus set in parallel to the response set when an appropriate face reference is provided, an overall up-right/down-left advantage suggestive of a continued influence of asymmetric coding still tends to be evident (Hommel & Lippa, 1995; Proctor & Pick, 1999).

In sum, our conclusion is that, at present, the best course of action for future research is to pursue development of more detailed explanations of both types of orthogonal SRC effects within a single framework. There are two reasons for this conclusion. First, the evidence clearly indicates that the coding asymmetry producing the overall up-right/down-left advantage is not restricted to verbal codes. Second, the results obtained for the type of orthogonal SRC effect that varies with hand and response position are in closer agreement with the predictions of coding accounts than with those of motor-system accounts. Orthogonal SRC effects are close relatives of parallel SRC effects, reflecting that response selection benefits from almost any type of correspondence between stimuli and their assigned responses. This benefit can be in terms of relative salience, as well as in terms of relative location along parallel dimensions. The current evidence suggests that motoric factors such as end-state comfort play at most a minor role in the orthogonal SRC effects. However, as is implied by Heister et al.'s (1990) hierarchical model of SRC, it is possible that responses may be coded in terms of motoric features for situations in which those features are particularly salient or spatial coding is not easily applicable.

Although orthogonal SRC effects are often small and less robust across a variety of experimental contexts than their parallel counterparts are, they provide fundamental insights into the nature of response selection. As recently as 22 years ago, the expectation was that neither of the two mappings should be more compatible than the other when stimuli and responses varied along orthogonal dimensions. Bauer and Miller's (1982) demonstrations of orthogonal SRC effects posed a challenge for accounts developed to explain spatial SRC that attribute it to spatial coding in response selection. Their conclusion was that coding accounts were not up to the task of explaining the orthogonal SRC effects. However, subsequent research has shown that the orthogonal SRC effects can be explained in terms of coding on the basis of salient features of the stimulus and response sets, as well as coding of the nominally orthogonal sets along parallel dimensions through the use of external objects as frames of reference. Salient-features coding is a factor in a variety of other SRC tasks, and coding with respect to aligned reference frames converts the orthogonal task environment into a typical, parallel, spatial SRC task environment. Thus, rather than being inexplicable in terms of coding accounts of response selection, the orthogonal SRC effects instead illustrate the pervasiveness of feature-based spatial coding in response selection.

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 & Performance*, **24**, 1582-1595.

Andre, A. D., Haskell, I., & Wickens, G. D. (1991). S–R compatibility effects with orthogonal stimulus and response dimensions. In *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 1546-1550). Santa Monica, CA: Human Factors Society.

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus–response compatibility in representational space. *Neuropsychologia*, **36**, 731-735.

Banich, M. T., & Federmeier, K. D. (1999). Categorical and metric spatial processes distinguished by task demands and practice. *Journal of Cognitive Neuroscience*, **11**, 153-166.

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

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, **94**, 115-147.

Biel, G. A., & Carswell, C. M. (1993). Musical notation for the keyboard: An examination of stimulus–response compatibility. *Applied Cognitive Psychology*, **7**, 433-452.

Bowerman, M. (1989). Learning a semantic system: What role do cognitive predispositions play? In M. L. Rice & R. L. Schiefelbusch (Eds.), *The teachability of language* (pp. 133-169). Baltimore: Paul H. Brookes.

Bradshaw, J. L., Bradshaw, J. A., & Nettleton, N. C. (1990). Abduction, adduction and hand differences in simple and serial movements. *Neuropsychologia*, **28**, 917-931.

Brady, N. (1997). Spatial scale interactions and image statistics. *Perception*, **26**, 1089-1100.

Brebner, J., Shephard, M., & Cairney, P. (1972). Spatial relationships and S–R compatibility. *Acta Psychologica*, **36**, 1-15.

Bridgeman, B. (1999). Separate representations of visual space for perception and visually guided behavior. In G. Aschersleben, T. Bachmann, & J. Müsseler (Eds.), *Cognitive contributions to the perception of spatial and temporal events* (pp. 3-13). Amsterdam: North-Holland.

Bridgeman, B. (2000). Interactions between vision for perception and vision for behavior. In Y. Rossetti & A. Revonsuo (Eds.), *Beyond dissociation: Interaction between dissociated implicit and explicit processing. Advances in consciousness research* (pp. 17-40). Amsterdam: John Benjamins.

Carlson-Radvansky, L. A., & Irwin, D. E. (1993). Frames of reference in vision and language: Where is above? *Cognition*, **46**, 223-244.

Chambers, K. W., McBeath, M. K., Schiano, D. J., & Metz, E. G. (1999). Tops are more salient than bottoms. *Perception & Psychophysics*, **61**, 625-635.

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 & Performance*, **27**, 472-484.

Cho, Y. S., & Proctor, R. W. (in press). Influence 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*.

Clark, H. H. (1973). Space, time, semantics and the child. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* (pp. 27-63). New York: Academic Press.

Clark, H. H., & Chase, W. G. (1974). Perceptual coding strategies in the formation and verification of descriptions. *Memory & Cognition*, **2**, 101-111.

Cooper, L. A., & Shepard, R. N. (1975). Mental transformation in the identification of left and right hands. *Journal of Experimental Psychology: Human Perception & Performance*, **1**, 48-56.

Cotton, B., Tzeng, O. J. L., & Hardyck, C. (1977). A response instruction by visual-field interaction: S–R compatibility effect or ? *Bulletin of the Psychonomic Society*, **10**, 475-477.

Cotton, B., Tzeng, O. J. L., & Hardyck, C. (1980). Role of cerebral hemispheric processing in the visual half-field stimulus–response compatibility effect. *Journal of Experimental Psychology: Human Perception & Performance*, **6**, 13-23.

Decety, J. (1996). The neurophysiological basis of motor imagery. *Behavioural Brain Research*, **77**, 45-52.

Dutta, A., & Proctor, R. W. (1992). Persistence of stimulus–response compatibility effects with extended practice. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 801-809.

Ehrenstein, W. H., Schroeder-Heister, P., & Heister, G. (1989). Spatial S–R compatibility with orthogonal stimulus–response relationship. *Perception & Psychophysics*, **45**, 215-220.

Farrell, W. W. (1979). Coding left and right. *Journal of Experimental Psychology: Human Perception & Performance*, **5**, 42-51.

Fitts, P. M., & Deininger, R. L. (1954). S–R compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, **48**, 483-492.

Garnham, A. (1989). A unified theory of the meaning of some spatial relational terms. *Cognition*, **31**, 45-60.

Hayward, W. G., & Tarr, M. J. (1995). Spatial language and spatial representation. *Cognition*, **55**, 39-84.

Heister, G., Schroeder-Heister, P., & Ehrenstein, W. H. (1990). Spatial coding and spatio-anatomical mapping: Evidence for a hierarchical model of spatial stimulus–response compatibility. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus–response compatibility: An integrated perspective* (pp. 117-143). Amsterdam: North-Holland.

Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory & Cognition*, **17**, 770-776.

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., & Lippa, Y. (1995). S–R compatibility effects due to context-dependent spatial stimulus coding. *Psychonomic Bulletin & Review*, **2**, 370-374.

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

Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review*, **99**, 480-517.

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

Klapp, S. T., Greim, D. M., Mendicino, C. M., & Koenig, R. S. (1979). Anatomic and environmental dimensions of stimulus–response compatibility: Implication for theories of memory coding. *Acta Psychologica*, **43**, 367-379.

Kleinsorge, T. (1999). Die Kodierungsabhängigkeit orthogonaler Reiz–Reaktions-Kompatibilität [Coding specificity of orthogonal S–R compatibility]. *Zeitshrift für Experimentelle Psychologie*, **46**, 249-264.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus response compatibility. A model and taxonomy. *Psychological Review*, **97**, 253-270.

Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate.* Cambridge, MA: MIT Press.

Kosslyn, S. M., Chabris, C. F., Marsolek, C. J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulations. *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 562-577.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 723-735.

Kosslyn, S. M., Maljkovic, V., Hamilton, S. E., Horwitz, G., & Thompson, W. L. (1995). Two types of image generation: Evidence for left and right hemisphere processes. *Neuropsychologia*, **33**, 1485-1510.

Kosslyn, S. M., Thompson, W. L., Gitelman, D. R., & Alpert, N. M. (1998). Neural systems that encode categorical versus coordinate spatial relations: PET investigations. *Psychobiology*, **26**, 333-347.

Làdavas, E. (1987). Influence of handedness on spatial compatibility effects with perpendicular arrangement of stimuli and responses. *Acta Psychologica*, **64**, 13-23.

Làdavas, E. (1988). Asymmetries in processing horizontal and vertical dimensions. *Memory & Cognition*, **16**, 377-382.

Làdavas, E., & Moscovitch, M. (1984). Must egocentric and environmental frames of reference be aligned to produce spatial S–R compatibility effects? *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 205-215.

Laeng, B. (1994). Lateralization of categorical and coordinate spatial functions: A study of unilateral stroke patients. *Journal of Cognitive Neuroscience*, **6**, 189-203.

Lamberts, K., Tavernier, G., & d'Ydewalle, G. (1992). Effect of multiple reference points in spatial stimulus–response compatibility. *Acta Psychologica*, **79**, 115-130.

Landau, B., & Jackendoff, R. (1993). "What" and "where" in spatial language and spatial cognition. *Behavioral & Brain Sciences*, **16**, 217-238.

Learmount, D., & Norris, G. (1990, October 31–November 6). Lessons to be learned. *Flight International*, pp. 24-26.

Lippa, Y. (1996). A referential-coding explanation for compatibility effects of physically orthogonal stimulus and response dimensions. *Quarterly Journal of Experimental Psychology*, **49A**, 950-971.

Lippa, Y., & Adam, J. J. (2001). An explanation of orthogonal S–R compatibility effects that vary with hand or response position: The end-state comfort hypothesis. *Perception & Psychophysics*, **63**, 156-174.

Lu, C. H., & Proctor, R. W. (1994). Processing of an irrelevant location dimension as a function of the relevant stimulus dimension. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 286-298.

Lu, C. H., & Proctor, R. W. (1998). Mapping effects for orthogonally oriented stimulus and response sets [abstract]. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (p. 165). Santa Monica, CA: Human Factors and Ergonomics Society.

Lu, C. H., & Proctor, R. W. (2001). Influence of irrelevant information on human performance: Effects of S–R association strength and relative timing. *Quarterly Journal of Experimental Psychology*, **54A**, 95-136.

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**, 342-348.

Michaels, C. F., & Stins, J. F. (1997). An ecological approach to stimulus–response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus–response compatibility* (pp. 333-360). Amsterdam: North-Holland.

Miller, R. R., & Grace, R. C. (2003). Conditioning and learning. In I. B. Wiener (Ed. in Chief) and A. F. Healy & R. W. Proctor (Vol. Eds.), *Handbook of psychology: Vol. 4. Experimental psychology* (pp. 357-397). New York: Wiley.

Nicoletti, R., Anzola, G. P., Luppino, G., Rizzolatti, G., & Umiltà, C. (1982). Spatial compatibility effects on the same side of the body midline. *Journal of Experimental Psychology: Human Perception & Performance*, **8**, 664-673.

Nicoletti, R., & Umiltà, C. (1989). Splitting visual space with attention. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 164-169.

Nicoletti, R., & Umiltà, C. (1994). Attention shifts produce spatial stimulus codes. *Psychological Research*, **56**, 144-150.

O'Leary, M. J., & Barber, P. J. (1993). Interference effects in the Stroop and Simon paradigms. *Journal of Experimental Psychology: Human Perception & Performance*, **19**, 830-844.

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

Olson, G. M., & Laxar, K. (1974). Processing the terms right and left: A note on left-handers. *Journal of Experimental Psychology*, **102**, 1135-1137.

Palef, S. R., & Olson, D. R. (1975). Spatial and verbal rivalry in a Stroop-like task. *Canadian Journal of Psychology*, **29**, 201-209.

Parsons, L. M. (1987a). Imagined spatial transformation of one's body. *Journal of Experimental Psychology: General*, **116**, 172-191.

Parsons, L. M. (1987b). Imagined spatial transformations of one's hands and feet. *Cognitive Psychology*, **19**, 178-241.

Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 709-730.

Perner, J., & Clements, W. A. (2000). From an implicit to an explicit "theory of mind." In Y. Rossetti & A. Revonsuo (Eds.), *Beyond dissociation: Interaction between dissociated implicit and explicit processing. Advances in consciousness research* (pp. 17-40). Amsterdam: John Benjamins.

Pouget, A., Fisher, S. A., & Sejnowski, T. J. (1999). Egocentric spatial representation in early vision. *Journal of Cognitive Neuroscience*, **5**, 150-161.

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

Proctor, R. W., & Cho, Y. S. (in press). Effect of relative position and response eccentricity on orthogonal stimulus–response compatibility with joystick and keypress responses. *Quarterly Journal of Experimental Psychology.*

Proctor, R. W., & Dutta, A. (1995). *Skill acquisition and human performance.* Thousand Oaks, CA: Sage.

Proctor, R. W., & Pick, D. F. (1999). Deconstructing Marilyn: Robust effects of face contexts on stimulus–response compatibility. *Memory & Cognition*, **27**, 986-995.

Proctor, R. W., & Reeve, T. G. (1985). Compatibility effects in the assignment of symbolic stimuli to discrete finger responses. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 623-649.

Proctor, R. W., & Reeve, T. G. (1986). Salient-feature coding operations in spatial precuing tasks. *Journal of Experimental Psychology: Human Perception & Performance*, **12**, 277-285.

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

Proctor, R. W., Reeve, T. G., & Van Zandt, T. (1992). Salient-features coding in response selection. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 727-741). Amsterdam: North-Holland.

Proctor, R. W., Reeve, T. G., Weeks, D. J., Campbell, K. C., & Dornier, L. (1997). Translating between orthogonally oriented stimulus and response arrays in four-choice reaction tasks. *Canadian Journal of Experimental Psychology*, **51**, 85-97.

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.

Reeve, T. G., & Proctor, R. W. (1984). On the advance preparation of discrete finger responses. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 541-553.

Reeve, T. G., Proctor, R. W., Weeks, D. J., & Dornier, L. (1992). Salience of stimulus and response features in choice-reaction tasks. *Perception & Psychophysics*, **52**, 453-460.

Rosenbaum, D. A. (1991). *Human motor control*. San Diego: Academic Press.

Rossetti, Y., & Pisella, L. (2002). Several "vision for action" systems: A guide to dissociating and integrating dorsal and ventral functions (tutorial). In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 62-119). Oxford, U.K.: Oxford University Press.

Roswarski, T. E., & Proctor, R. W. (1996). Multiple spatial codes and temporal overlap in choice-reaction tasks. *Psychological Research*, **59**, 196-211.

Rubichi, S., Nicoletti, R., Iani, C., & Umiltà, C. (1997). The Simon effect occurs relative to the direction of an attention shift. *Journal of Experimental Psychology: Human Perception & Performance*, **23**, 1353-1364.

Sekiyama, K. (1982). Kinesthetic aspects of mental representations in the identification of left and right hands. *Perception & Psychophysics*, **32**, 89-95.

Seymour, P. H. K. (1969). Response latencies in judgements of spatial location. *British Journal of Psychology*, **60**, 31-39.

Sholl, M. J., & Egeth, H. E. (1981). Right–left confusion in the adult: A verbal labeling effect. *Memory & Cognition*, **9**, 339-350.

Simon, J. R. (1969). Reaction toward the source of stimulation. *Journal of Experimental Psychology*, **81**, 174-176.

Stoffer, T. H. (1991). Attentional focussing and spatial stimulus–response compatibility. *Psychological Research*, **53**, 127-135.

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

Umiltà, C., & Liotti, M. (1987). Egocentric and relative spatial codes in S–R compatibility. *Psychological Research*, **49**, 81-90.

Umiltà, C., & Nicoletti, R. (1985). Attention and coding effects in S–R compatibility due to irrelevant spatial cues. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 457-471). Hillsdale, NJ: Erlbaum.

Umiltà, C., & Nicoletti, R. (1990). Spatial stimulus–response compatibility. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus–response compatibility: An integrated perspective* (pp. 89-116). Amsterdam: North-Holland.

Virzi, R. A., & Egeth, H. E. (1985). Toward a translational model of Stroop interference. *Memory & Cognition*, **13**, 304-319.

Vu, K.-P. L., & Proctor, R. W. (2002a). *Mixing compatible and incompatible mappings: Elimination, reduction, and enhancement of spatial compatibility effects*. Manuscript submitted for publication.

Vu, K.-P. L., & Proctor, R. W. (2002b). The prevalence effect for two-dimensional S–R compatibility is a function of the relative salience of the dimensions. *Perception & Psychophysics*, **64**, 815-828.

Wallace, R. J. (1971). S–R compatibility and the idea of a response code. *Journal of Experimental Psychology*, **88**, 354-360.

Wang, H., & Proctor, R. W. (1996). Stimulus–response compatibility as a function of stimulus code and response modality. *Journal of Experimental Psychology: Human Perception & 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. (1991). Salient-features coding and orthogonal compatibility effects: A reply to Umiltà. *Journal of Experimental Psychology: General*, **120**, 87-89.

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.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, **68**, 77-94.

Wightman, F. L., & Kistler, D. J. (1997). Factors affecting the relative salience of sound localization cues. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and spatial hearing in real and virtual environments* (pp. 1-23). Mahwah, NJ: Erlbaum.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 397-412.

Zhang, J., & Kornblum, S. (1997). Distributional analysis and De Jong, Liang, and Lauber's (1994) dual-process model of the Simon effect. *Journal of Experimental Psychology: Human Perception & Performance*, **23**, 1543-1551.

NOTES

1. The emphasis of this account is on maintaining structural correspondence between the asymmetric coding of the stimulus set and the asymmetric coding of the response set. One might propose that the more "salient" members of the stimulus and response sets are identified faster than the less salient members, leading to a prediction that within the up-right/down-left mapping, performance would be better with the up-right S–R pairing than with the down-left S–R pairing. Such a result is not typically observed, which suggests that what we are calling the more salient member of the respective sets does not "pop out" faster than the less salient member. Rather, there is a response-selection benefit for both members of the stimulus and response sets when the salience structure of the stimulus set is mapped directly to that of the response set.

2. Ehrenstein, Schroeder-Heister, and Heister (1989) also demonstrated an effect of hand posture for a task that required pressing the index or middle finger of a single hand oriented orthogonally with respect to left and right stimulus locations. Their study was an orthogonal variation of the Simon task for which stimulus location was irrelevant. Because our concern in the present article is with the mapping of relevant location information to responses, we will not discuss their study in detail.

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