STIMULUS-RESPONSE COMPATIBILITY
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SPATIAL CODING AND SPATIO-ANATOMICAL MAPPING: EVIDENCE FOR A HIERARCHICAL MODEL OF SPATIAL STIMULUS-RESPONSE COMPATIBILITY

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Spatial stimulus-response (S-R) compatibility usually denotes the reaction-time (RT) advantage for spatially compatible S-R pairings over incompatible pairings in choice-reaction tasks. This notion goes back to Fitts and Seeger (1953), who credited the term "compatibility" to a suggestion by A. M. Small. It is difficult to give a definition that captures everything that has been associated with this term. Quite generally, one may call S-R pairings spatially compatible if, with respect to a certain spatial characteristic, the stimuli and responses correspond to each other and incompatible if they have opposite spatial characteristics.

A typical example of spatial compatibility is the situation in which subjects react to a light stimulus in the right or left visual field by pressing a right or left response button with their right or left hand, respectively. One normally finds a spatial S-R compatibility effect, in the sense that right-hand reactions to right lights and left-hand reactions to left lights (compatible condition) are faster than right-hand reactions to left lights and left-hand reactions to right lights (incompatible condition; Brebner, Shephard, & Cairney, 1972; Craft & Simon, 1970; Simon & Wolf, 1963; Wallace, 1971; upright head conditions of Ládavas & Moscovitch, 1984, Experiments 1 and 3, and of Schroeder-Heister, Heister, & Ehrenstein, 1988).[1] Usually it is not specified whether this effect

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[1]There is a certain ambiguity in the notion of S-R compatibility. By S-R compatibility, one may designate (1) a feature of the experimental stimulus-response arrangement whose effect on which performance is measured (i.e., an independent variable, which is experimentally manipulated); (2) the effect that compatible responses are faster than incompatible responses (i.e., an observed result); (3) a certain interpretation of this compatibility effect emphasizing its cognitive character as opposed, e.g., to neuroanatomic explanations (see Heister & Schroeder-Heister, 1985). In the following, it will always be clear from the context what is meant.

means (a) that the right hand reacts faster to the right light than to the left light, and the left hand faster to the left light than to the right light, (b) that the right hand reacts faster than the left hand to the right light, and the left hand faster than the right hand to the left light, or (c) both of these possibilities.

Similar examples could be given for stimuli in the upper and lower visual fields (Ládavas & Moscovitch, 1984, upright head conditions of Experiments 1 and 4; Nicoletti & Umiltá, 1984; Nicoletti, Umiltá, Tressoldi, & Marzi, 1988) and for auditory stimulation (Simon 1969; Simon & Rudell, 1967; see also Chapter 2, by Simon). However, because the pattern of results is similar for these different experimental conditions, in the following section, in which some basic results of compatibility research are to be discussed, we will mainly deal with the paradigm of bimanual choice reactions to right and left lights. Our considerations can be extended to most other S-R arrangements in a straightforward way. For the sake of simplicity, we will also refrain from distinguishing between spatial S-R compatibility effects for relevant stimulus location, for which the subject's task concerns the spatial distinction that is in question for the compatibility effect, and irrelevant stimulus location, for which the task concerns responding to some other feature of the stimulus (such as its color or its semantic content).

What is Compatible or Incompatible in Spatial S-R Compatibility?

With bimanual choice reactions to right and left stimuli, there are at least three different right/left distinctions on the response side, leading to three different relations between stimuli and responses. First, we have a right/left distinction between the *positions of the response keys*. Then, we can distinguish between the right or left *position of the responding hand*. And, finally, there is the anatomical distinction between *the right and the left hand*. Correspondingly, the compatibility effect observed may be due to the compatibility or incompatibility of either (a) stimulus position and response key position, (b) stimulus position and response effector position, or (c) stimulus position and responding hand. Obviously, all three possibilities are confounded in the normal paradigm, in which the *right key* is operated with the *right hand* held in *right position*.

The confounding between responding hand and its position was resolved by Simon, Hinrichs and Craft (1970b--auditory stimulation) and independently by Wallace (1971--visual stimulation). In these studies, subjects reacted with their arms crossed, so that the right hand was placed on the left side and the left hand was placed on the right side. The compatibility between stimulus position and the position of responding hand (or response key), and not the compatibility between stimulus position and right or left hand, was shown to be crucial for the observed effect. (For applications of this technique, see Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977; Brebner et al., 1972; Callan, Klisz, & Parsons, 1974; Nicoletti, Anzola, Luppino, Rizzolatti, & Umiltá, 1982.)

Riggio, Gawryszewski, and Umiltá (1986) resolved the confounding between position of response keys and position of responding hand. They studied responses with hands held in right or left positions, with only the responding index fingers crossed, so that subjects pressed the left key with their right-index finger and the right key with their left-index finger. The compatibility between stimulus position and position of response keys, and not between stimulus position and position of responding hand, caused the observed compatibility effect. This result was confirmed by an experiment in which subjects used crossed sticks to press the response buttons, so that even the index fingers of the responding hands were on their normal right or left sides. Because Riggio et al.'s (1986) paper was the first study that explicitly dealt with the hand-position/key-position distinction (Klapp, Greim, Mendicino, & Koenig, 1979, Experiment 1, dealt with it implicitly, see later), the empirical basis for this distinction is still relatively small. In particular, no investigation has been carried out for irrelevant stimulus location.

On the stimulus side, too, there is at least one confounding, namely between apparent location of the stimulus and the sensory organ stimulated. Craft and Simon (1970, Experiment 2) used stereoscopic presentation of stimuli to show that the compatibility effect disappears if the apparent position of the stimulus is in the middle of the visual field, although actually either the right or the left eye is stimulated. Therefore, on the stimulus side, the *apparent* position of the stimulus is essential for S-R compatibility. Analogous results were also obtained for auditory stimulation, using phase transformation to produce an apparent right/left location with binaural stimulus presentation (Simon, Craft, & Small, 1971; Simon, Small, Ziglar, & Craft, 1970a).

The results from the above-mentioned studies show that spatial S-R compatibility is related to the compatibility between perceived stimulus position and the position of the response key. However, in most designs, the apparent and actual stimulus positions, as well as the positions of the responding hands and response keys, are the same. Thus, we will treat the relation between stimulus position and response position as essential for spatial S-R compatibility. In other words, the central distinction on the response side that we are addressing in this paper is that between *response position* (which may be key position or hand position) and *response effector* (e.g., anatomically defined right or left hand). The distinction between hand position and key position will nevertheless be included in the hierarchical model proposed subsequently.

Several explanations have been proposed to account for the importance of spatial positions. According to Simon, the stimulus perceived is a command to react in a certain way, namely, to press the right or left button. Because, as a "population stereotype" (Simon & Rudell, 1967, p. 300), a "'natural' tendency to respond toward the source of stimulation" (Simon, 1969, p. 174) is assumed, there is the "necessity of overriding this initial response tendency" (Simon et al., 1970a, p. 314) when the content of the command (i.e., the locus of the correct response) does not agree with the locus of the stimulus source, yielding longer RTs. In earlier papers, Simon had considered this stereotype to express an orienting reflex (Simon, 1968, 1969), but he later abandoned this interpretation because such an effect should very quickly disappear with practice, which is not true for the spatial S-R compatibility effect (see Simon, 1970; Faber, van der Molen, Keuss, & Stoffels, 1986). Furthermore, Simon did not claim that this natural tendency is "natural" in the strict sense: "It might very well be learned" (Simon, 1970, p. 51).

According to Wallace (1971), spatial S-R compatibility is due to a comparison of spatial codes for stimulus and response positions, leading to longer RTs when the representations of stimulus and response positions do not coincide. This coding interpretation resembles Fitts and Seeger's (1953) theory that S-R compatibility is related to the rate of information transfer in reaction tasks. Later researchers have further advanced Wallace's coding interpretation of spatial S-R compatibility (in particular, Nicoletti et al., 1982; Nicoletti & Umiltá, 1984, 1985; Umiltá & Nicoletti, 1985; Umiltá & Liotti 1987; see Chapter 3 by Umiltá & Nicoletti). However, whereas these latter researchers saw a fundamental distinction between Simon's approach, which they called "attentional" (Nicoletti et al., 1982; we followed this perhaps unfortunate terminology in Heister, Ehrenstein, & Schroeder-Heister, 1986, 1987), and the coding hypothesis, Wallace did not. Rather, he regarded his coding theory as a more abstract basis for Simon's "tendency to respond toward the source of stimulation" (see Wallace, 1971, p. 360).

With respect to the stage of cognitive processing in which S-R compatibility effects are generated, the major position is that the response-selection stage, rather than the stimulus-encoding stage, is relevant (cf. Sanders, 1980). This hypothesis is supported by results using Sternberg's (1969) additive factors paradigm (see Acosta & Simon, 1976; Callan et al., 1974; Simon, 1982; Simon, Acosta, & Mewaldt, 1975; Simon, Acosta, Mewaldt, & Speidel, 1976). However, there is also some evidence concerning the importance of the stimulus side, in particular the dependence of the size of the observed effect on the distance of the stimuli (Ehrenstein, Heister, & Schroeder-Heister, in preparation; Gunia, 1987; Rabbitt, 1967; Simon et al., 1971).

In the following, we will refer to the coding hypothesis as the major theoretical explanation of spatial S-R compatibility, while being aware that "coding" has a rather vague meaning. We understand "coding hypothesis" to be used mainly as a label for theories assuming that spatial S-R compatibility is a genuinely cognitive phenomenon that has to do with the internal representation of spatial relationships.

Unimanual Two-Finger Choice Reactions

Standard designs for studying spatial S-R compatibility typically investigate bimanual reactions to lateralized visual or auditory stimuli. Sometimes unimanual movement reactions have also been employed, such as moving a handle to the right or left (Simon 1968, 1969) or moving the index finger from a starting location to one of two response buttons (Bauer & Miller, 1982; Brebner, 1979; Cotton, Tzeng, & Hardyck, 1980; Hedge & Marsh, 1975). Results from Katz (1981) indicate that spatial S-R compatibility effects also are obtained between stimulus locations and the two fingers of one hand. In an experiment with irrelevant stimulus location and unimanual reactions, with the hand held in a middle position, Katz showed that compatible visual field/finger pairings (e.g., stimulus in the right field, response with the right finger) were faster than incompatible ones, independent of which hand was used for responding. In the following, we will call this kind of spatial S-R compatibility *finger compatibility*, as distinguished from *hand compatibility*. In the context of unimanual two-finger choice reactions, hand-compatibility effects denote RT advantages for compatible field/hand relations that may be obtained in addition to finger-compatibility effects. These latter effects are probably present in most data for choice reactions with two or more fingers, but are usually not evaluated.

The Comparison of Prone and Supine Hand Orientations

In several experiments we have investigated compatibility effects with two-finger choice reactions, placing particular emphasis on the distinction between spatial and anatomical factors. To distinguish between spatial and anatomical influences, an analog to the crossed-arms test of the bimanual case had to be developed. In Heister et al. (1986, 1987), we used the comparison between prone hand position (response buttons pressed as usual from above) and supine hand position (response buttons pressed from below). When the hand is turned, the spatial relations between the responding fingers are reversed: The finger that is spatially right with the hand held prone is spatially left in the supine hand. Comparing the finger-compatibility effects for both positions can therefore indicate whether the observed effect is due to the position of the responding finger or to some anatomical relation. These possibilities were confounded in Katz's (1981) experiment.

Results for relevant stimulus location. The main question of our first study (Heister et al., 1986) was whether a spatial S-R compatibility effect occurs with two-finger choice reactions when the palms are facing down and whether it persists when the hands are turned over. Eight female subjects had to react toward a right or a left light with the index or middle finger of their right or left hand, whereby the responding hand was held in a normal right or left position. The results showed a clear-cut finger-compatibility effect when the palms were facing down and an even more pronounced effect when the palms were facing up.

These results support the coding hypothesis of spatial S-R compatibility, which says that the relative spatial positions of stimuli and responses are encoded and compared irrespective of the anatomical response organs. Any explanation of the results relying on callosal crossing time (pathway hypothesis) is immediately refuted because the movements of two fingers of one hand are initiated within the same hemisphere. Because both responses are given on the same side of the body midline, the results cannot be explained by the tendency to react towards the source of stimulation (at least not without making an ad hoc extension of this hypothesis). Finally, no right/left classification of the anatomical fingers can account for these results, because the spatial compatibility effect persisted for hands in supine position. That is, such a classification is reversed by turning the hands and, therefore, would predict the converse effect with the palm-up position.

No hand-compatibility effect was observed in addition to the strong finger-compatibility effect, although the responding hand was held in lateral rather than middle position, opposed to Katz's (1981) design. This negative result may be explained by the fact that the experimental task did not demand a choice between responding hands (which were only changed between blocks of trials), but between the responding fingers of one hand.

Results for irrelevant stimulus location and fixed versus alternating hands. In a subsequent study (Heister et al., 1987), spatial S-R compatibility effects for two-finger choice reactions were investigated for irrelevant stimulus location. Tests also were included for determining whether additional hand-compatibility effects would be obtained with irrelevant stimulus location and whether such effects may depend on holding the responding hand fixed throughout an experimental session. Eight new female subjects responded with their index or middle finger to a bicolor diode that emitted either red or green light in the right or left visual field. The subjects were tested with the palms facing down and the palms facing up, with the responding hand being altered in both conditions between blocks of trials. They also were tested with the palms facing down, but with the same hand being used throughout an experimental session. The results showed a strong finger-compatibility effect for all three conditions.

The tendency for the finger-compatibility effect to increase from the palm-down condition (with alternating hands) to the palm-up condition, which was already present in the previous study (Heister et al., 1986), now became statistically significant. As in the previous study, no hand-compatibility effect occurred in the conditions with alternating hands. In the condition with nonalternating hands, however, an additional, small hand-compatibility effect was obtained.

These results again suggest the prevalence of the spatial coding factor in S-R compatibility, because the compatibility effect for fingers depends on the relative spatial positions of the responding fingers with respect to each other and not on their anatomical relation. The small hand-compatibility effect for the condition with the responding hand being fixed throughout an experimental session can be explained by a modified attentional hypothesis. According to this hypothesis, constant use of one hand directs more attention toward the corresponding side of stimulation. However, the empirical basis for this hand-compatibility effect is still too small to allow for more than a tentative hypothesis. Experimental work to elucidate this effect is being performed presently (Schroeder-Heister, Ehrenstein, & Heister, in preparation).

Spatial Versus Anatomical Finger Distance

Another experiment with two-finger choice reactions tested the hypothesis that the size of the spatial S-R compatibility effect is distance-dependent with respect to the response. That is, we investigated whether and in what manner the compatibility effect changes if the relative distance of responses is altered. As an alternative to the supine hands test, such an investigation should discriminate between coding of response positions and anatomical right/left classification of fingers, if one distinguishes between the *spatial distance* of the response buttons and the *anatomical distance* of the responding fingers. An example of anatomical distance is that the second and fourth fingers are nearer to each other than are the first and fifth, even if they operate the same pair of buttons. If the size of the observed compatibility effect only depends on the spatial distance and not on the anatomical distance, one may infer that spatial coding is the effective factor. If the size of the observed effect only depends on the anatomical distance and not on the spatial distance, then an anatomical right-left discrimination can be concluded to be essential. Further possibilities are that the size of the compatibility effect depends on both spatial and anatomical distance, or that there is no distance-dependence at all.

Therefore, the question of the following experiment was whether the finger compatibility effect remains stable when the response is given with different spatial and different anatomical distances between responding fingers. In our previous studies, we used index and middle fingers for response, but now we chose the second (index) and fourth finger (ring) or the first (thumb) and fifth (little) finger, respectively, so that the third (middle) finger could be regarded as the middle of the responding hand. To vary spatial and anatomical distance between fingers independently, in one of the experimental conditions subjects placed their first and fifth finger on response buttons at a narrow separation that would normally be used for their second and fourth fingers.

Six right-handed female college students (aged 17 to 19 years) served as subjects. The stimuli were two red light-emitting diodes, positioned at 5° of visual angle to the left and right of the fixation point and presented for 100 ms. Response keys were two circular microswitches, whose centers were separated by 45 mm (narrow box) or by 110 mm (wide box); these distances were average results for hand measurements taken of the subjects in advance: The narrow box was used for the index-finger/ring-finger condition and for the thumb/little-finger, narrow spacing condition; the wide box was used for the thumb/little-finger wide (or natural) spacing condition.

The subjects attended two sessions on different days. In one session they responded with their right hands, in the other session with their left hands. In each session, three conditions were investigated: (a) index-finger/ring-finger operating the narrow buttons, (b) thumb/little-finger operating the wide buttons, and (c) thumb/little-finger operating the narrow buttons. The three conditions were tested in a sequence of six blocks of trials (i.e., two blocks for each condition), each consisting of six practice trials followed by 60 test trials (30 in the right field, 30 in the left field). In three blocks of each session, the subjects made spatially compatible responses; in the other three blocks, they made spatially incompatible responses. So as not to draw their attention to spatial relations, the instructions were in terms of index-, ring-, little fingers, or thumbs, rather than left or right position of the fingers. Errors were few, and error trials were repeated at the end of each block.

Mean RTs were subjected to an analysis of variance, with response condition (a, b, c), responding hand (right/left), field of stimulus presentation (right/left), and responding finger (right/left) as within-subject factors (see Table 1 for cell means and corresponding standard deviations). There were two significant main effects, one for experimental condition, $F(2, 10) = 4.61$, $p < .05$, and one for field of stimulus presentation, $F(1, 5) = 49.52$, $p < .001$. Responses were fastest with second and fourth finger (Condition a: 281 ms) and slowest with first and fifth finger pressing the narrow buttons (Condition c: 293 ms). Reactions were overall faster with right-field than with left-field stimulation (283 vs. 293 ms), which might be interpreted as expressing a left-hemisphere superiority for spatial decision tasks and is in agreement with our previous results for S-R designs with relevant stimulus location (Heister et al., 1986). The significant interaction between field and responding finger, $F(1, 5) = 87.47$, $p < .001$, expresses the S-R compatibility effect for fingers. There was a significant change in the size of this compatibility effect between the different response conditions, as indicated in the three-way interaction between response condition, field of stimulation, and finger, $F(2, 10) = 9.06$, $p < .01$ (see Figure 1).

Table 1

Mean Reaction Times (in milliseconds) and Standard Deviations for Experimental Condition a (second and fourth fingers operating narrow buttons), Condition b (first and fifth fingers operating wide distance buttons), and Condition c (first and fifth fingers operating narrow buttons)

	Left light		Right light	
	Responding finger			
	Left	Right	Left	Right
	Condition a			
Right hand	264 (37)	310 (39)	304 (49)	254 (29)
Left hand	259 (25)	314 (22)	300 (40)	245 (15)
	Condition b			
Right hand	272 (28)	321 (37)	299 (43)	259 (28)
Left hand	290 (46)	295 (34)	292 (42)	282 (28)
	Condition c			
Right hand	266 (30)	315 (35)	311 (51)	265 (43)
Left hand	282 (41)	324 (27)	315 (46)	266 (23)

Note. The numbers in parentheses are standard deviations.

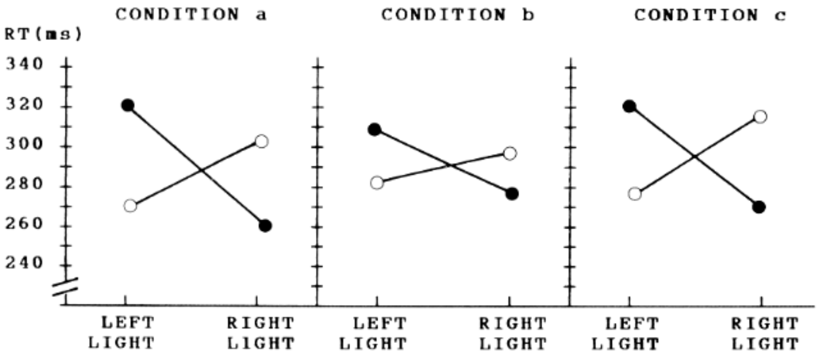

Figure 1. Mean RTs for responses to lights in the right or left visual field with the right (filled circles) and left fingers (unfilled circles), averaged over both hands. Condition a: Second and fourth fingers operating narrow buttons; Condition b: First and fifth fingers operating wide distance buttons; Condition c: First and fifth fingers operating narrow buttons.

Under Condition b, in which the wide-distance buttons were pressed with the first and fifth fingers, the compatibility effect was significantly smaller than in the other conditions (difference between incompatible and compatible reactions in Condition a: 51 ms, Condition b: 26 ms, Condition c: 46 ms; see Figure 1). Because this was especially true for left hand responses, the interaction between response condition, hand, field, and finger was significant, $F(2, 10) = 7.57$, $p = .01$. A significant difference in the compatibility effect between right and left hands took place only in Condition b, in which the first and fifth fingers operated the wide-distance buttons (interaction between hand, field, and finger for this condition: $F(1, 5) = 11.21$, $p < .05$). Further research to clarify why this effect took place only for left-hand responses is being performed.

The most interesting result is that there was no difference in the size of the S-R compatibility effect for Condition a (index finger/ring finger--narrow buttons) and Condition c (thumb/little finger--narrow buttons), which differ with respect to anatomical finger distance, but not with respect to spatial finger distance. This means that the anatomical distance of the responding fingers alone is not relevant for the size of the compatibility effect. But there was a significant difference between Condition b (thumb/little finger--wide buttons) and Condition c (thumb/little finger--narrow buttons), which differ with respect to spatial finger distance, but not with respect to anatomical finger distance (interaction between condition, field, and finger in the subanalysis for data of Conditions b and c: $F(1, 5) = 15.49$, $p = .01$). The S-R compatibility effect was smaller when thumb and little finger pressed the wide buttons than when they pressed the narrow buttons, which means that only the spatial (environmental) distance of the responding fingers seems to be relevant to the size of the effect. Therefore, we can conclude that the spatial S-R compatibility effect for two-finger choice reactions itself essentially depends on the purely spatial rather than anatomical relations of the responses.

Spatial Coding and Spatio-Anatomical Mapping

The Effectiveness of Subordinate Factors

When the spatial right/left distinction *on the stimulus side* is eliminated by arranging the stimulus along the spatial top/down dimension, but response buttons are still on the right or left side, then the compatibility effect disappears (see Simon & Wolf, 1963; Soetens, Deboeck, Hueting, & Merckx, 1984; Wallace 1971, 1972--nevertheless, there may be an association of dominant hand with top position, see Ládavas, 1987). However, a compatibility effect may be obtained when *on the response side* the right/left distinction for response keys is eliminated, but stimulus lights are still on the right or left side, because for the responses other right/left distinctions (i.e., position of response effector or anatomical classification) still remain in force.

Klapp et al. (1979, Experiment 1--crossed and uncrossed conditions) had subjects operate a single switch, which was mounted in a middle position, with their thumbs from the right or left side, and observed a spatial-compatibility effect (RT advantage for compatible hand-light relations). By performing this experiment with crossed and uncrossed arms, Klapp et al. made sure that the effect was not due to the anatomical status of the hands as right or left but to the position of the responding hand.

Furthermore, when the right/left distinction for response keys, as well as for positions of responding hands, is eliminated, a compatibility effect is observed for which the anatomical status of the responding hand as right or left is relevant. Again, experiments by Klapp et al. (1979) can be used as evidence: They had subjects respond to left and right stimuli, with hands held in the up/down dimension, by operating a single button with their respective thumbs. A highly significant interaction between (right or left) field of stimulation and (anatomically right or left) responding hand was found both for uncrossed and crossed arms (Klapp et al., 1979, Experiment 1, up/down condition with stimulus location relevant; Experiment 2, experimental condition with stimulus location irrelevant). These findings also were obtained when subjects lay on their sides and the spatial right/left positions of the responding *arms* were eliminated (Klapp et al., 1979, Experiment 3). These results show that those spatial relations that are subordinate to the basic stimulus position/response-key position relation (i.e., the stimulus-position/response-effector position relation and the stimulus-position/anatomical-hand relation) can be effective.

A corresponding result for finger compatibility was obtained in our study with two-finger choice reactions and orthogonal S-R relations (Ehrenstein, Schroeder-Heister, & Heister, 1989). The main question was whether, under conditions in which no direct right-left association of stimulus positions and positions of response effectors is possible, an anatomical right/left classification of responding fingers becomes essential. For this purpose, an experimental design was chosen in which stimuli and responses were perpendicular to each other. In four different sessions, subjects reacted to red or green lights in the right or left visual field (irrelevant stimulus location) by pressing response keys that were arranged in the following ways: (a) on the right or left side of the body midline (control condition), (b) perpendicular to the stimuli horizontal in the midsaggital plane, (c) same as in Condition b but pressed from below (supine hand position), and (d) perpendicular to the stimuli vertical in the midsaggital plane, pressed with the palms facing the body.

The results for Condition a (the control condition) showed the usual spatial S-R compatibility effect for field of stimulus presentation and responding finger. For Conditions b and d, a strong S-R compatibility effect was found for the same stimulus/finger pairings. For Condition c, that is, reactions with supine hand position, RT advantages for the opposite stimulus/finger pairings were obtained. This means that those stimulus/finger relations were faster than they would be if one turned the hand back into the normal right or left position (while keeping its prone or supine orientation). These findings strongly support the hypothesis that an anatomical right/left distinction becomes effective if the right/left distinction between response *positions* is eliminated. The shift of this relation under Condition c can be interpreted as showing that, unlike the case of the right and left hands, there is no canonical right/left classification of anatomical fingers. That is, this classification may depend on hand orientation (prone vs. supine).

One might suppose that the effectiveness of the anatomical right/left distinctions found by Klapp et al. (1979) could be explained by neuroanatomical connectivity. However, the effects observed are much higher than standard estimates of the callosal crossing time and have the size of a standard compatibility effect for which the positions of response keys are important. Furthermore, they only are obtained, at least in the size observed, if there is a choice reaction between the responding hands. If there is no choice between the responding hands, a compatibility effect for hands is, if existent at all, very small (see Klapp et al., 1979, Experiment 2). And, finally, our results with orthogonal S-R relations refute this hypothesis, because the responses of two fingers of one hand are initiated from the same hemisphere.

This suggests that the observed anatomical right/left effects are cognitively based, as are the other S-R compatibility effects mentioned. One may hypothesize that there is a coding of the right and left hand as spatially right and left, respectively. This code is based on the fact that the anatomically right and left hands are spatially right and left, when the hands are held in normal positions on the respective sides of the body. This code is then kept, even when the hands are held in non-normal positions, that is, in middle positions or on opposite sides of the body. One may also speak of a "natural association" of the anatomically right and left hands as spatially right and left. Correspondingly, for two-finger choice reactions, we may assume that there are codes for anatomical fingers as right or left (even if these codes are not unique and canonical as for right and left hands), and that these codes are kept even when the response keys are not mounted parallel to the stimuli.

To avoid confusion, we propose the term *spatio-anatomical mapping* (in short: mapping) for this association of spatial positions with anatomical distinctions, and reserve the term *spatial coding* for the coding of response *positions*. We wish to emphasize here the cognitive character of spatio-anatomical mapping, which is not explicitly stated in Heister et al. (1986), where this term was introduced.[2]

Evidence for spatial S-R compatibility effects in situations for which the response keys are not oriented along the right/left dimension can also be found in neuropsychological investigations of cerebral functioning, which we illustrate by some data of our own.

Compatibility Effects With Orthogonal S-R Relations in Divided-Visual-Field Studies of Cerebral Lateralization

Because S-R compatibility effects take place not only with relevant stimulus location but also with irrelevant location, compatibility might affect every normal divided visual-field study of cerebral lateralization in which choice reactions are required to stimuli in the right or left visual field. Therefore, the RT asymmetry (field effect), which usually is used as an indicator of the nature of hemispheric processing, is difficult to interpret because of potential S-R compatibility effects.

We first obtained evidence for such joint effects of cerebral lateralization and S-R compatibility by replicating a lexical decision task under three different response conditions: (a) normal unimanual two-finger choice reactions, with the hands positioned on the right and left sides; (b) unimanual two-finger choice reactions, with the response keys positioned one behind the other along the midline of the experimental desk (medial position); (c) vocal responses (see Heister & Schroeder-Heister, 1987). The experiment with lateral response position (a) showed a hand-compatibility effect that significantly decreased with medial response position (b).[3]

Therefore, in a subsequent study on hormonal influences on hemispheric processing during the menstrual cycle (Heister, Landis, Regard, & Schroeder-Heister, 1989), we tried to exclude such possible additional S-R compatibility effects by placing the response buttons (for bimanual reactions) one behind the other in medial position (i.e., orthogonal to the stimuli along the midline of the experimental desk). In this way, the right/left distinction for positions of response keys was eliminated. However, in view of the results reported in the previous section, this arrangement might not be able to fully eliminate S-R compatibility, because a distinction between right and left hand is still possible. Therefore, a reanalysis of the data from this experiment is presented, which focuses on compatibility effects. The basic hypothesis is that spatial S-R compatibility effects still are obtained in addition to cerebral effects and hormonal influences.

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[2]The possible cognitive representation of anatomical distinctions is also taken into consideration by Guiard (1984, p. 20).

[3]Because of the initial main interest in interhemispheric relations, finger-compatibility effects were not evaluated in Heister and Schroeder-Heister (1987).

Twelve normally menstruating females aged 22 to 39 years took part in two experiments, one lexical-decision task (function words vs. nonsense syllables) and one analogously constructed face-decision task (photographically produced composites of normal vs. scrambled faces). Half of the subjects gave yes-decisions with the farther button and no-decisions with the nearer one, and the other half had the reversed relation. The stimuli were presented for 130 ms in the right or left visual field. Every subject took part four times in every experiment in four different phases of the menstrual cycle. Three subjects started in each of the four cycle phases (for a more detailed description see Heister et al., 1989).

In Heister et al. (1989), the data were evaluated with respect to phase of menstrual cycle without considering the responding hand as a separate factor. The following reanalysis presents the data grouped with respect to order of test sessions (session 1 to session 4) and effects of responding hands (right vs. left). This reanalysis may also answer the question of whether practice and experience with the tasks influence a possible S-R compatibility effect. For each of the two experiments (verbal and non-verbal), an analysis of variance was conducted for means of the correct RTs with test session (1 to 4), field of stimulus presentation (right/left), and responding hand (right/left) as within-subject factors. Only relevant data are presented here.

In the lexical-decision experiment, in addition to an overall practice effect (linear decrease of RTs from session 1 to session 4) and a right field (left hemisphere) superiority, a significant interaction was obtained between test session, field and hand, $F(3, 33) = 3.43$, $p < .05$. There was an S-R compatibility effect in the first test session (compatible reactions [right field/right hand, left field/left hand] being 57 ms faster than incompatible ones), which disappeared during the replications and even shifted to the opposite in the last session, in which incompatible reactions were 14 ms faster than compatible ones (see Figure 2).

The analysis for the face-decision experiment also showed a practice effect and, as expected, a left field (right hemisphere) superiority. In addition, there was a significant interaction between field of stimulus presentation and responding hand, $F(1, 11) = 6.52$, $p < .05$. This interaction expresses an overall S-R compatibility effect, with compatible responses being 15 ms faster than incompatible ones (see Figure 3).

With small S-R compatibility effects, one can always object that they were actually pathway effects. However, in the present case this could not explain why the effect disappeared in the lexical-decision task after the first session and even shifted in the last session, because pathway effects should reflect hardware and, thus, should be stable.

In general, these divided visual-field studies of cerebral lateralization showed evidence for S-R compatibility effects for the responding hand, although the response buttons were in the midsaggital plane and thus orthogonal to the stimuli, and the position of the stimuli was irrelevant for the decision. In addition, there were differences between the lexical-decision and the face-decision task that might have to do with differences in task difficulty: For the more difficult task (face decisions), the S-R compatibility effect did not change during four retest sessions, whereas it did for the easier task (lexical decisions).

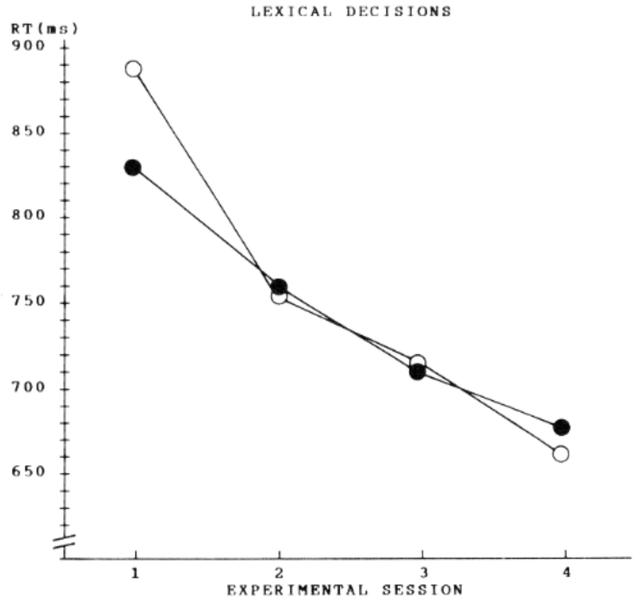

Figure 2. Mean RTs for responses to verbal stimuli for compatible (filled circles) and incompatible (unfilled circles) field-hand relationships for experimental sessions 1 to 4.

Our results support the hypothesis that spatio-anatomical mapping becomes effective if spatial coding of response positions is excluded by arranging response keys perpendicular to the stimuli. One might object that not the anatomical right/left distinction, but rather the spatial position of responding hands (which were still on the right or left side, even though the response buttons, being pressed with the index fingers, were mounted in middle position) was essential for the effect observed. However, even if this objection is correct, which cannot be decided on the basis of the data available, the results show that hand position, as distinguished from key position, can be effective.

Finally, the results confirm the claim that spatial S-R compatibility not only is obtained with low-level tasks (such as right/left or red/green discrimination) but also with higher-level tasks (such as lexical or face decisions)--a topic that has not yet been given appropriate attention in compatibility research. This means that in neuropsychological studies of this kind, spatial S-R compatibility effects cannot be totally ruled out.

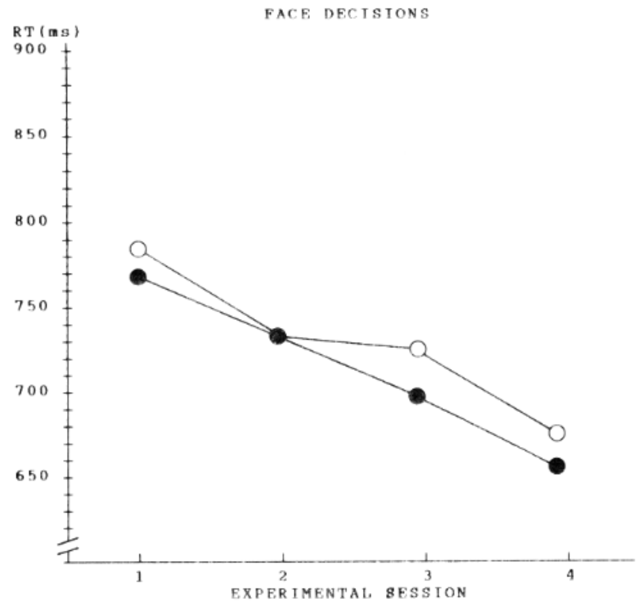

Figure 3. Mean RTs for responses to non-verbal stimuli for compatible (filled circles) and incompatible (unfilled circles) field-hand relationships for experimental sessions 1 to 4.

A Hierarchical Model of Spatial S-R Compatibility

The Three Factors and Their Rank Order

We have distinguished three kinds of compatibility that differ with respect to the spatial coding of the response: (a) compatibility due to the coding of positions of response keys (*coding of key position*), (b) compatibility due to the coding of positions of responding hands or fingers (*coding of effector position*), and (c) compatibility due to the coding of the response effectors as right or left (*spatio-anatomical mapping*). According to the results reported, which of these compatibilities is effective in a given situation is not an unpredictible function of the response conditions that are used in an experimental design. Rather, their appearance follows a clear pattern: Coding of key position is the dominant factor (see Riggio et al., 1986). However, if such a coding is impossible (as in Klapp et al., 1979, Experiment 1, crossed and uncrossed conditions, for which there was no spatial difference between the response goals), then spatial coding of effector position becomes the dominant factor. Furthermore, if an appropriate coding of positions of response effectors is likewise impossible (as in Klapp et al., 1979, Experiment 1, up/down condition, for which stimuli were in right/left position but responding hand in up/down position, or in the orthogonal S-R arrangements for two-finger choice reactions of Ehrenstein et al., 1988), then spatio-anatomical mapping becomes the dominant factor.

Thus, we propose a model that assumes a hierarchical order of the following factors: (a) spatial coding of response keys, (b) spatial coding of effector positions, (c) spatio-anatomical mapping. These factors jointly determine spatial S-R compatibility. Factor (a) is dominant over factors (b) and (c), and factor (b) is dominant over (c). However, if one factor is not applicable, then the factor of next lower rank becomes the dominant one. This approach, which develops further an idea by Klapp et al. (1979) on anatomical and environmental dimensions of S-R compatibility, enables us to treat spatial S-R compatibility as a uniform phenomenon that is determined by several factors which become effective according to their rank order.

The hierarchical model proposed is certainly not fully exhaustive. It puts particular emphasis on distinctions between ways of coding spatial relations on the response side. Distinguishing ways of coding spatial relations on the stimulus side may lead to an extension of the model. What we propose is only a first attempt to overcome the situation that "after more than twenty [now: thirty] years' research there is no metric for compatibility that transcends particular experimental conditions" (Welford, 1980, p. 99).

Interactions Between the Factors of the Hierarchical Model

The hierarchical model and its rank order were motivated by the results that show that a certain type of compatibility becomes relevant if certain others are not applicable. However, there are also results that suggest that the different factors do interact. This means that the factors of the model not only replace each other following a certain rank order, but can jointly determine an observed effect (by preserving this order).

With respect to spatial coding versus spatio-anatomical mapping, the results and theoretical proposals by Nicoletti, Umiltá, and Ládavas (1984) on the slowing down of reactions with crossed arms can be interpreted in that way. They showed that with simple RTs there is no slowing down of reactions if the responding hand is held on the opposite side of the body midline. They concluded that the longer overall RTs usually observed under crossed-arms conditions is due to a mismatch between the spatial codes of hand and hand position and, thus, is a cognitive phenomenon.

The same theorizing applies to the slowing down of reactions observed for supine as compared to prone hand orientation in our experiments with two-finger choice reactions. Because turning the hands causes a reversal of the spatial order of the anatomical fingers, this slowing down of reactions can be attributed to a mismatch between spatial codes of anatomical fingers and finger positions. However, it was statistically significant only with relevant stimulus location (Heister et al., 1986), showing a non-significant trend with irrelevant stimulus location (Heister et al., 1987). This may be due to the fact that anatomical right/left codes are not so obvious and uniquely determined for responding fingers as for responding hands. A nearly significant increase of RTs under the supine hand condition was also observed in Ehrenstein et al. (1988, Condition c), where response keys were arranged perpendicular to the stimuli, so that no appropriate spatial code for the finger positions could be formed. Here this increase may be due to a mismatch between different anatomical finger codes for prone and supine orientation. However, results are not yet available with simple RTs for prone vs. supine hand orientation, by means of which one could clearly distinguish between a cognitive effect due to a mismatch between different codes and a purely bio-mechanical difference between the two hand orientations.

Even the generally slower reaction for the condition in which the first and fifth fingers pressed the narrow buttons (the finger-distance experiment reported in this chapter) might be interpreted in a similar way. In this condition, a mismatch may be seen as occurring between the codes of a narrow spatial distance and a wide anatomical distance, leading to the overall increase of RTs. However, this idea must be considered very tentatively, because an explanation that simply refers to the mechanical difficulty of the task has not been experimentally excluded.

Analogous hypotheses can be applied to Riggio et al.'s (1986) results on the slowing down of reactions with crossed fingers or crossed sticks. These findings may be considered as being due to a mismatch between the spatial codes for response goals and position of response effectors. (Riggio et al. themselves explained the findings by a mismatch between the spatial codes for response goals and the anatomical right/left distinction.)

Our referral to "interaction" of factors of the hierarchical model is justified in the strict statistical sense. When we consider the paradigm of bimanual reactions, the slowing down of reactions under the crossed-arms condition can be interpreted as a main effect of experimental condition, as an interaction between responding hand and its position, and as an interaction between compatibility with respect to hands and compatibility with respect to their positions, depending on how factors are grouped in the analysis of variance. Suppose that in a hypothetical experiment, we obtained the data displayed in Table 2 as results for right-hand and left-hand reactions to right and left lights with uncrossed and crossed arms. Then, we can first interpret these data as expressing a main effect for experimental condition (uncrossed vs. crossed arms). Second, we can arrange them as in the upper panel of Table 3, interpreting them as an interaction between hand and hand position (as in the studies of Nicoletti et al., 1984, and Brebner et al., 1972). Finally, however, we may arrange them as in the lower panel of Table 3. With respect to this arrangement, we can interpret the data as expressing an interaction between stimulus-hand compatibility and stimulus-hand position compatibility (i.e., between factors (b) and (c) of our hierarchical model.) This means that the field-hand position compatibility effect, which is due to spatial coding, takes place essentially only under a compatible field-hand relation. This arrangement of data was proposed by Simon et al. (1970b) and also used by Callan et al. (1974).

In the following, we put particular emphasis on the relations between factors (a) and (b) on the one side and factor (c) on the other, that is, the relation between coding of response key or effector position and spatio-anatomical mapping.

Table 2

Reaction Times in a Hypothetical Experiment for Right Hand (RH) and Left Hand (LH) Responses to Right and Left Lights for the Experimental Conditions of Arms Held Uncrossed and Arms Held Crossed

Condition	Left Light		Right Light		Mean
	LH	RH	LH	RH	
Uncrossed	300	350	350	300	325
Crossed	400	350	350	400	375

Table 3

Arrangement of the Data of Table 2 According to the Factors Hand and Hand Position (upper panel), and According to the Factors Stimulus-Hand Compatibility and Stimulus-Hand Position Compatibility (bottom panel)

Hand Position	Hand	
	Left	Right
Left	325	375
Right	375	325

Stimulus-Hand Position Compatibility	Stimulus-Hand Compatibility	
	Compatible	Incompatible
Compatible	300	350
Incompatible	400	350

Direct Effects of Spatio-Anatomical Mapping

So far we have dealt with the case in which spatial coding is replaced by spatio-anatomical mapping if coding is undefined, and with the case where coding is the major factor, but mapping *indirectly* influences coding by interacting with it. The latter produces a slowing down of reactions under crossed-arms or supine-hand conditions. However, there are also situations in which coding is possible in principle (i.e., is not undefined), but mapping replaces coding or is at least *directly* effective by not only influencing overall RTs but also qualitatively or quantitatively impairing the coding effect itself. Ládavas and Moscovitch's (1984) results can be taken as an example of coding being replaced by mapping, although a coding hypothesis makes sense. Schroeder-Heister et al. (1989) showed that mapping can inhibit coding without fully eliminating it.

In several experiments, Ládavas and Moscovitch (1984) studied the relation between head tilt and frames of reference by investigating three conditions of head position: head held upright, tilted 90° to the right, and tilted 90° to the left. In the tilted-head conditions, stimuli and responses were always perpendicular to each other, with either the stimuli arranged along the horizontal dimension and the (bimanual) responses along the vertical dimension or vice versa. In half of the experiments, the responding hands were exchanged, similar to the crossed-arms test. Ladavas and Moscovitch found an association between stimuli and responding *hands* (not *hand positions*) of the following pattern: There was an RT advantage for those stimulus-hand pairings that correspond to each other if the stimulus is encoded as right or left in the appropriate frame of reference (environmental vs. egocentric) that makes a right/left distinction possible. This result is explained by the idea that under the conditions of the given experimental design, the coding of response positions was replaced by the coding of the anatomical right/left classification, that is, by spatio-anatomical mapping in our terminology.[4] This replacement of spatial coding by spatio-anatomical mapping took place although a sort of spatial coding is imaginable in principle: One may, for example, assume that the positions of stimuli and responses are coded in different frames of reference, arriving either at a top/down or right/left classification for both stimuli and responses (see Ládavas & Moscovitch, 1984, Discussion of Experiments 1 and 2).[5]

To resolve the confound between head tilt and orthogonality of stimuli and responses in Ládavas and Moscovitch's study, we investigated the condition of head tilted alone (Schroeder-Heister et al., 1989). We had subjects react under the conditions of head held upright, head tilted to the right, and head tilted to the left (as in Ládavas & Moscovitch, 1984), but with stimuli always arranged horizontally and responses being given always by two buttons mounted on the right or left side of the experimental desk. Subjects were tested both with uncrossed and with crossed arms. In the upright head condition, the usual spatial S-R compatibility effect between stimulus position and response position was obtained for both uncrossed and crossed arms. In the tilted-head conditions, this effect was still present, but significantly decreased from the uncrossed-arms to the crossed-arms conditions, without reversing to

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[4]Ládavas and Moscovitch (1984) vacillate between the interpretation that it is essentially the condition of head tilt under which spatial coding is replaced by spatio-anatomical mapping (p. 213, bottom of left column and bottom of right column) and the interpretation that head tilt in combination with orthogonality of stimuli and responses is responsible for the observed effect (p. 214, top of right column).

[5]Ládavas and Moscovitch's (1984) results also seem to express a tendency towards a slowing down of reactions with exchanged hands, which may indicate an indirect influence of spatial coding in addition to the dominant effect of spatio-anatomical mapping. However, this cannot be exactly established on the basis of the published data.

the opposite. In other words, with crossed arms, RTs were not only overall slower, but the size of the spatial-compatibility effect was diminished.

By not using experimental condition (arms uncrossed vs. crossed) but instead hand compatibility and position compatibility as factors in the analysis of variance (see the hypothetical experiment discussed above and Tables 2 and 3), the results for the tilted-head conditions can also be interpreted as follows: Both a significant position-compatibility effect and an (anatomical) hand-compatibility effect were obtained, as was a significant interaction between these effects. This shows that besides coding of response positions, which remains the dominant factor, spatio-anatomical mapping can be *directly* present, now reducing the coding effect under the crossed-arms condition. The interaction of coding and spatio-anatomical mapping expresses again the *indirect* influence of mapping by increasing the overall RTs in the crossed-arms condition. We explained this result as indicating that spatial coding of response positions is particularly difficult when both the head is tilted and the arms are crossed, leading to a greater uncertainty in coding spatial positions as right or left.

Because our results show that head tilt alone does not eliminate spatial coding of response positions as the dominant factor, the additional difficulty in stimulus encoding (choice of an appropriate frame of reference) in Ládavas and Moscovitch's (1984) experiments may lead subjects to rely on the clear anatomical right/left distinction for their responses. This would mean that *response* encoding may also depend on the conditions of *stimulus* encoding, because these are the only essential differences between our design and Ládavas and Moscovitch's design for the horizontal response arrangement.

The findings of Ládavas and Moscovitch (1984) and Schroeder-Heister et al. (1989) fully support our hierarchical model. In a situation where spatial coding is made difficult, spatio-anatomical mapping has the chance to interfere or, under extremely difficult conditions, even to dominate over spatial coding.

Some Methodological Remarks

In the present paper, we have placed our main emphasis on the response side of spatial S-R compatibility, distinguishing between various ways of coding the response: coding of positions of response keys, coding of positions of responding hands or fingers, and coding of (anatomically right or left) hands or fingers, that is, spatio-anatomical mapping. Correspondingly, the techniques considered to separate influences of the various factors were manipulations of the response arrangement. One of the basic experimental methods to distinguish between purely spatial and spatio-anatomical aspects of S-R compatibility is a comparison between data for arms held in normal position and for arms crossed. There is a general difficulty with interpreting such data that has implications far beyond the crossed-arms paradigm.

According to one possible interpretation, uncrossed-arms vs. crossed-arms are experimental conditions whose influence on the manner of cognitive processing is experimentally investigated. If a difference in performance is observed when the arms are held crossed, this difference is interpreted as expressing a change in cognitive processing. For example, the overall slowing down of reactions in crossed-arms conditions can be interpreted as reflecting a cognitive conflict between anatomical and spatial codes that is not present when the arms are held normally, but that arises when the arms are crossed.

According to another interpretation, the crossed-arms condition is just a measurement device of the experimenter to distinguish between effects due to hand and to hand position, without affecting cognitive procedures. A change in performance with arms crossed is not interpreted as expressing a change in information processing, but as revealing features of its permanent structure that cannot show up, although present, with hands in normal position. Taking the same example as above, the slowing down of reactions with arms crossed is interpreted as indicating some general interaction of anatomical and spatial codes that is always present, but manifests itself in a specific way when the arms are crossed.

One may try to distinguish experimentally between these two interpretations by providing a baseline condition "between" uncrossed and crossed arms. If the crossed-arms test is a condition that changes processing by causing a cognitive conflict between spatial and anatomical codes, an inhibition of processing should be expected with arms crossed. However, if the crossed-arms test is nothing but a methodological instrument demonstrating a *permanent* cognitive interference of anatomical and spatial codes, processing should not just be inhibited if both codes are incongruent (i.e., under the crossed-arms condition), but also facilitated if both codes are congruent (i.e., under the uncrossed-arms condition). Without detailed discussion, Klapp et al. (1979, Experiment 1) implicitly investigated this question by studying a baseline in their up/down condition (hands operating a button from above and below), which they used in addition to their crossed/uncrossed conditions (hands operating a button from the right or left side with arms crossed or arms uncrossed). The overall RTs in the crossed-arms condition were significantly larger (by nearly 100 ms) than in both the uncrossed-arms and the up/down conditions, whereas there was practically no RT difference between the uncrossed-arms and the up/down condition. This indicates that there is inhibition of processing under the crossed-arms condition, but no facilitation under the uncrossed-arms condition. Thus, one may conclude that something actually "happens" internally when one crosses arms. That is, the crossed-arms test manipulates the manner of processing.

However, studying baseline conditions like the one just mentioned, which is a rather neglected topic in compatibility research, cannot fully eliminate the basic difficulty. In principle, one cannot exclude that this baseline condition itself represents an experimental manipulation that may change processing and thus requires another ("higher order") baseline condition to establish whether it is in fact a neutral condition between the uncrossed- and crossed-arms conditions, and so forth *ad infinitum*.

Obviously, this problem occurs not just with the crossed-arms test in compatibility experiments, but with all sorts of changes of the response arrangements that are undertaken either to isolate or to exclude anatomy-related factors as relevant for an observed effect. Besides the crossed-arms test, we have particularly discussed the comparison between prone and supine hand positions and the distinction between anatomical and spatial finger distance. Related questions can be posed if one wants to use the crossed-arms methodology to establish effects due to neuroanatomical connectivity (see Anzola et al., 1977; Berlucchi, Crea, Di Stefano, & Tassinari, 1977; Bradshaw & Umiltá, 1984; Levy, 1984). It seems that the only way to cope with these difficulties, at least in part, is to consider baseline conditions on the stimulus side (e.g., by presenting stimuli in middle position) independently of manipulations on the response side.

What we are facing here with respect to S-R compatibility is the general problem of experimental methodology: Certain methods of observation change what is observed in a way essential for the purpose of the investigation.

Summary

A consideration of different right/left relations on the response side distinguishes at least three types of spatial S-R compatibility: (a) compatibility between stimulus positions and positions of response keys, (b) compatibility between stimulus positions and positions of response effectors (hands or fingers), and (c) compatibility between stimulus positions and anatomically right or left response effectors. Compatibilities of types (a) and (b) may be attributed to an internal coding of response positions (called "spatial coding") and compatibility of type (c) to an internal coding of anatomical right/left classifications (called "spatio-anatomical mapping").

Standard results in compatibility research show that spatial coding is dominant in determining compatibility effects and that anatomy-related factors play a subordinate role. For bimanual choice reactions this has been established by the crossed-arms test, whereas it has been established for unimanual two-finger choice reactions by comparing prone and supine hand orientations. As a further possibility to separate spatial from anatomical factors in unimanual two-finger choice reactions, we propose the distinction between anatomical and spatial finger distance. Preliminary experimental data presented here show that the size of the compatibility effect varies with spatial and not with anatomical finger distance.

Notwithstanding the priority of spatial coding, several results show that spatio-anatomical mapping may be effective if spatial right/left distinctions on the response side are eliminated. In particular, mapping is effective if response buttons are arranged in middle position perpendicular to the stimuli. This conclusion is also supported by the reanalysis of data of a divided visual-field study of cerebral lateralization.

To integrate the seemingly divergent findings, we have proposed a hierarchical model, according to which spatial S-R compatibility is a joint result of the three factors mentioned above, which dominate each other according to a certain rank order and which can interact in various ways.

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