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Must Egocentric and Environmental Frames of Reference Be Aligned to Produce Spatial S-R Compatibility Effects?

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Four experiments were conducted to determine the effects of misaligning egocentric and environmental frames of reference on spatial S-R compatibility effects. In Experiments 1 and 3, subjects looked at two lights that were aligned horizontally, one each on either side of the body midline. They held their head upright or tilted 90° to the left or right. In the upright condition the hands were uncrossed and rested opposite the lights (frames of reference aligned), whereas in the head tilt condition the hands were either crossed or uncrossed but positioned perpendicular to the lights (frames of reference not aligned). Manual choice reaction times to the lights produced spatial S-R compatibility effects that were as large when the frames of reference were aligned as when they were not. In Experiments 2 and 4, which also used upright and tilted conditions, we found generally similar results when the lights were displayed vertically and the hands disposed horizontally. The results indicate that under conditions of head rotation and with stimulus and response arrays perpendicular to each other, spatial S-R compatibility effects still occur. By taking into account both frames of reference, the subject classifies the stimuli as left or right whether they are horizontally or vertically disposed and maps them onto the responding hand, thereby producing the observed compatibility effects.

In several choice reaction time (RT) tasks employing an array of stimuli and an array of responses, certain stimulus-response (S-R) pairings lead to faster RTs than others. The more efficient S-R associations are termed compatible and the less efficient, incompatible. One of the most common types of S-R compatibility is based on the relationship between the spatial attributes of the signals and the responses (Fitts & Seeger, 1953). This "spatial compatibility" (S-R) effect is typically seen when the selection of the response is directly based on the position of the stimulus. Thus if there are two light stimuli, one in the right visual field and the other in the left, and two response keys, one on the right and the other on the left, RT is faster when the task requires that the right key be pressed in response to the right flash and the left key be pressed in response to the left flash, as compared to a task involving the opposite S-R pairings (Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977; Brebner, Shepard, & Cairney, 1972). A different variety of spatial compatibility effect is the so-called "Simon effect," which can be observed in RT tasks where the position of the stimulus is in itself irrelevant for the selection of the response and yet has a systematic influence on responding speed. For example, if the right key has to be pressed in response to a lateralized stimulus of a particular shape or color, and the left key has to be pressed in response to another lateralized stimulus of a different shape or color, the response is faster when the stimulus and the appropriate key are on the same side and slower when they are on opposite sides of the midline, even though response selection is not contingent on stimulus position (Simon, Sly, & Vilapakkan, 1981; Wallace, 1971).

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Different explanations have been offered to account for these different spatial S–R compatibility effects. Simon and associates (Simon, 1968, 1969; Simon, Craft, & Small, 1970) have produced much evidence to support the notion that the locus of the stimulus influences the choice of the direction of a motor response insofar as responses toward the stimulus are usually faster than responses away from the stimulus. Wallace (1971, 1972) put forward a more comprehensive interpretation of spatial S–R compatibility effects. This incorporates Simon's notion of a stereotypic tendency to react toward the source of the stimulus into a more general model of sensorimotor integration whereby the correspondence between the position of the stimulus and the felt (proprioceptive) position of the responding part of the body (e.g., a hand) is the crucial factor that facilitates compatible responses.

Thus, a stimulus and a response are considered compatible when their respective positions can be matched according to some spatial code, as suggested by the fact that spatial compatibility and incompatibility effects can be observed even in the absence of an overt spatial coincidence between stimulus displays and responses. For example, Nicoletti, Anzola, Luppino, Rizzolatti, and Umiltà (1982) measured choice RT in a situation in which there were two possible stimuli horizontally arranged in one visual field and two horizontally disposed response keys on the side of the midline opposite the visual field. Because in both the stimulus set and the response device set one member of the set could be classified as right and the other as left, independent of the position of the set with respect to the midline, subjects were faster in responding with the right key to the right light and with the left key to the left light, as compared to right-left and left-right S–R associations.

These compatibility effects can hardly be explained by the natural tendency to respond toward the source of the stimulus, nor can they be attributed to the contiguity between stimulus and locus of response. In the present study we further explored the generation of differential S–R associations based on the correspondence between the spatial code describing the position of the stimuli and that describing the spatial attributes of the response effectors. More specifically, we studied choice RT under complex conditions where the subject had the choice of adopting more than one spatial code for classifying the position of either the stimuli or the response mechanisms. In addition, we eliminated all directional or proximity cues assumed to mediate the Simon effect so that S–R compatibility effects found under these conditions would have to be ascribed to a matching between the code for the stimuli and that for the responses. It is known that there are two spatial codes for describing the position of the visual stimuli: environmental, or physical frame of reference, and the egocentric, or retinal frame of reference. When the head is in the normal upright position, the two frames of reference coincide, that is, what is "up" in one frame is also "up" in the other frame. But if the subject tilts his or her head to the right or the left by 90°, the two frames of reference no longer coincide because what is "up" in the physical frame of reference is "left" (respectively, "right") in the egocentric frame of reference, and so on for the other positions. Thus, a subject with his or her head rotated can use two codes, one egocentric and the other physical, for describing any position in the visual space. Attneave and Olson (1967) and Attneave and Reid (1968) reported that under conditions of head rotation, people normally tend to use the physical rather than the egocentric frame of reference in order to map responses onto the spatial attributes of stimuli. The egocentric frame of reference, however, can be promptly adopted under instruction or by spontaneous decision.

Experiments 1 and 2

When a subject has to press the right key in response to the right light and the left key in response to the left light, his or her reactions are faster than those based on the opposite S–R couplings (Anzola et al., 1977; Brebner et al., 1972). Similarly, if both lights and keys are arranged vertically, the choice of the top key for the top light and the bottom key for the bottom light is quicker than the opposite choices (Nicoletti & Umiltà, 1983). Consider now a situation in which the two lights are disposed horizontally, but the subject tilts his or her head to the right by 90° so that the right light is in his or her upper visual field, and the left light is in his or her lower visual field. The keys are also rotated with the head so that the right key is now below the head and the left key is above it (see Figure 1a). According to the environmental frame of reference, the two lights are classified as left and right, and the two keys are classified as top and bottom; whereas according to the egocentric frame of reference, the two lights are classified as top and bottom, and the two keys are classified as right and left. Within either code, the description of the lights' positions does not correspond in any way to that of the keys' positions, in agreement with the fact that in real space each key is equidistant from the two lights. Therefore, the adoption of either code for classifying *both* the lights' positions *and* the keys' positions should not be expected to result in S–R compatibility and incompatibility effects. An alternative outcome is possible if the subject uses two frames of reference simultaneously—for example, the environmental frame of reference for classifying the lights' positions and the egocentric frame of reference for classifying the keys' positions or, alternatively, the egocentric frame of reference for classifying the lights' positions and the physical frame of reference for classifying the keys' positions. In either case, the stimuli and the response will share the same spatial code. Specifically, there will be a right light and a right key and a left light and a left key in the first case as well as a top light and a top key and a bottom light and a bottom key in the second case. Similar S–R couplings, but with reverse associations, would apply if the subject tilted the head to the left rather than to the right (see Figure 1b).

As a result, a choice RT experiment employing all possible combinations between stimuli and responses should produce compatibility and incompatibility effects and should be predictable on the basis of the strategy employed by the subjects. This hypothesis was tested in Experiment 1. Experiment 2 tested the same hypothesis in a situation in which the stimuli are arranged vertically and the two keys horizontally.

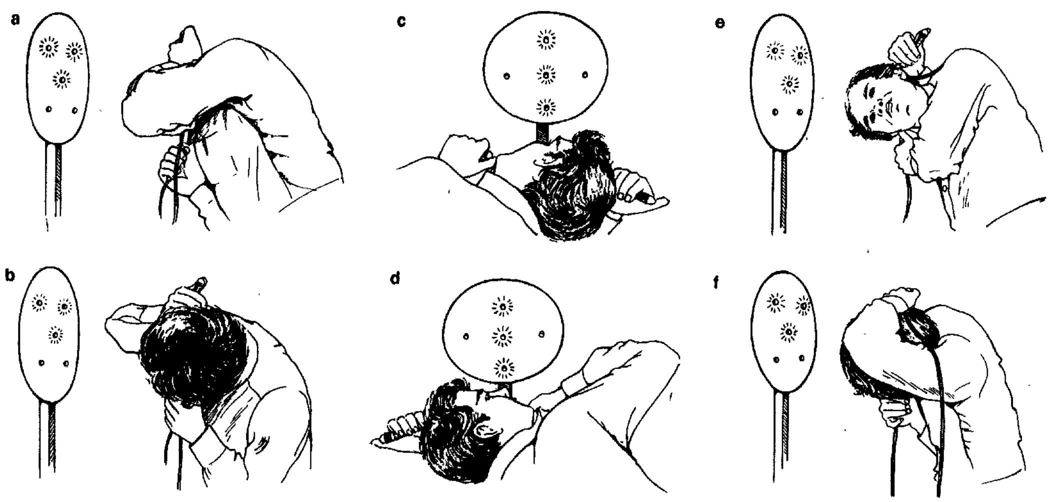

Figure 1. Panels a and b: Subjects with the head tilted 90° to the right in Panel a and 90° to the left in Panel b. (Note the line joining the hands is meant to be perpendicular to the horizontal. Only the two lights above fixation were used in this experiment. For clarity of exposition, the table on which the subject rested his head was removed, and the exact disposition of the lights in relation to the subjects was slightly altered. Panels c and d: Subject with his head tilted 90° to the right in Panel c and 90° to the left in Panel d. The line joining the two hands is meant to be perpendicular to the vertical. Only the two lights on the vertical line that passes through the fixation point were used in this experiment. Panels e and f: Subjects with head tilted 90° to the right in Panel e and 90° to the left in Panel f. This photograph is identical to Panels a and b except that the hands are crossed with respect to their position in Panels a and b.)

Experiment 1

Method

Subjects. Six students of the University of Toronto, three males and three females, between the ages of 18 and 27 participated in the experiment for course credit. They were all right-handed, as assessed on the basis of the Briggs and Nebes (1975) questionnaire, had normal or corrected-to-normal vision, and were naive as to the purpose of the experiment.

Apparatus. Each subject sat inside a dark and sound-proof cubicle in front of a panel displaying three light-emitting diodes (LEDs). The head, resting on a horizontal wooden board, was either upright or tilted 90° to the right or left. The distance between the eyes and the midpoint of the panel was 50 cm. A central, green LED served as a fixation point, and two red LEDs served as stimuli. They were located on either side at and above the fixation point at a 45° angle from the horizontal plane and passing through it. Each LED was 11.5 cm from the fixation point and subtended a visual angle of about 0.57°. When activated, it emitted a pulse of red light that lasted 100 ms and had an intensity of 27.22 cd/m^2 (see Figure 1).

Each hand held a plastic cylinder equipped with a push button on its top. When the head was in the upright position, the two hands holding the cylinders rested on the desk beside the head, with the right hand in front of the right light and the left hand in front of the left light. When the head was in the tilted position, the two hands were placed in contact with the sides of the head, the right hand with the right side and the left hand with the left side so that the hands were lined up with the vertical midline of the display panel. A special-purpose computer for the presentation of the stimuli and the recording and analysis of the responses was located in a room adjacent to the cubicle.

Procedure. The trials were arranged in a quasi-random sequence so that the probability of occurrence of a left or right light on each trial was equal; the only restriction was that no more than three consecutive trials could occur on one side. A warning signal was provided by lighting the fixation LED 1-3 s prior to each stimulus presentation. The subject was instructed to press one of the keys upon the appearance of a given light. All possible combinations between lights and keys were tested. Each subject attended two experimental sessions that were run on consecutive days. Each session consisted of six blocks of 10 practice trials and 60 experimental trials per block, with a 10-min rest period between consecutive blocks. In each session, subjects were tested under three conditions of head position: upright, tilted to the right, and tilted to the left. All six possible orders of head position were used and counterbalanced across subjects. Subjects followed the same order in both sessions. Within each session two conditions of S–R pairings were tested for each head position, giving rise to six possible combinations that corresponded to the six blocks in the session. In each of the three head positions, the two conditions of S–R pairings were the following. When the head was upright, one S–R pairing involved pressing the right key for the right light and the left key for the left light; the other S–R pairing involved pressing the right key to the left light and the left key to the right light. When the head was tilted to the right, one S–R pairing involved pressing the key below the head (right hand) to the right light and the key above the head (left hand) to the left light; the other S–R pairing involved the opposite associations. When the head was tilted to the left, one S–R pairing involved pressing the key below the head (left hand) to the left light and the key above the head (right hand) to the right light; the other S–R pairing involved the opposite associations. The order of S–R pairing conditions was counterbalanced across sessions and across subjects.

In order to avoid any verbal influence on the subject's pattern of response, the instructions prior to each block were given simply by pointing with a rod to the stimulus to which a given hand responded as well as to the hand itself.

RTs were measured from the onset of the light stimulus to the appropriate key press; only RTs longer than 100 ms and shorter than 1000 ms were collected. Trials in which subjects responded incorrectly and/or RTs were outside the above limits were not repeated.

Results

A preliminary inspection of the data showed no systematic difference between the results of different sessions. Thus mean RT was computed across sessions for each subject for each of the 12 conditions resulting from the combinations between the three head positions (upright, left-tilted, and right-tilted) and the four associations between the side of the stimulus (right or left) and the responding hand (right or left). Because errors never exceeded 5% of the trials and were distributed uniformly across these 12 conditions, each subject provided 12 basic scores, each of which was the mean of a minimum of 57 and a maximum of 60 RTs. The means across subjects for the 12 basic conditions are shown in Table 1.

It is clear from the table that independent of head position, the right hand was faster in reacting to the right stimulus than to the left, and the left hand was faster in reacting to the left stimulus than to the right. When the head was upright, right-hand responses were on the average 46 ms faster for the right stimulus than for the left stimulus, and left-hand responses were 39 ms faster to the left stimulus than to the right. The corresponding differences for the condition in which the head was tilted to the right were 41 ms for the right hand and 57 ms for the left hand. In the condition in which the head was tilted to the left, the corresponding differences were 51 ms for the right hand and 13 ms for the left hand. All subjects showed this pattern of results. An analysis of variance using head position, side of stimulus, and responding hand as main factors showed a significant effect of head position, $F(2, 10) = 6.12, p < .02$, with the head upright condition yielding faster RTs than the others. The interaction between side of stimulus and responding hand, $F(1, 50) = 39.5, p < .002$, was also significant. Paired t tests showed that in all head positions the ipsilateral hand/side of stimulus associations (right hand/right stimulus, left hand/left stimulus) produced significantly faster RTs than the contralateral hand/side of stimulus associations, $.001 < p < .05$ in all cases.

Experiment 2

Experiment 2 was identical to Experiment 1 except that the positions of lights and responses were interchanged. Six new subjects, 3 males and 3 females selected as in Experiment 1, took part in the experiment.

Method

Apparatus. The apparatus was the same as that described for Experiment 1, except that the two LEDs were above and below the fixation point at a distance of 11.5 cm.

Procedure. As in Experiment 1, each head condition (upright, left-tilted, and right-tilted) comprised two conditions of S–R pairing. When the head was upright, one hand was above and the other below the table. They were aligned with the midsagittal plane of the body and equidistant from the fixation point. In one condition the subject was required to respond to the top light with the top hand and to the bottom light with the bottom hand, whereas in the other condition the assignment was reversed so that the top light corresponded to the bottom hand and vice versa. In each condition, half of the responses were given with the right hand above and the left one below and half with the opposite hand assignment.

When the head was tilted 90° to the right, the keys were placed so that the left hand was under the chin (bottom) and on the left of fixation point, while the right hand was on the top of the head (top) and on the right of the fixation point. Both keys were at the same distance from the green light and perpendicular to an imaginary line passing between the two stimulus lights (see Figure 1c).

In one condition the subject was required to respond with the bottom hand (or left) to the upper (or left) stimulus and with the top hand (or right) to the lower (or right) stimulus. In the other condition the subject had to respond with the bottom hand (or left) to the lower (or right) stimulus and with the top hand (or right) to the upper (or right) stimulus.

When the head was tilted to the left, the two conditions were the same except that the right hand remained on the right of fixation but was now under the chin, whereas the left hand remained on the left of the fixation but was now on the top of the head (see Figure 1d). As in Experiment 1, the order of conditions was counterbalanced across sessions and subjects.

Results

Mean RT was calculated across sessions for each subject for each of the 12 conditions resulting from the combination between the side of the stimulus (above and below), the position of the responding hand (above and below), and the position of the head (upright, left, right). The means across subjects for the 12 basic conditions are shown in Table 2. An analysis of variance using head position, side of stimulus, and responding hand as main factors showed that only the Head Position × Side of Stimulus × Responding Hand Position interaction was significant, $F(2, 10) = 10.7, p < .004$. Paired t tests showed that the 44-ms advantage for the top hand over the bottom hand when responding to the upper stimulus and the 40-ms advantage of the bottom hand over the top hand when responding to the lower stimulus were both significant ($p < .05$).

In the right-tilted condition, RT for the bottom hand (or left in the physical frame of reference) was 20 ms faster for the upper stimulus (or left) than for the lower one. All subjects showed this effect, which was significant ac-

Table 1
Reaction Time (in ms) as a Function of Head Position, Stimulus Position, and Position of the Responding Hand: Experiment 1

	Head upright			Head right-tilted			Head left-tilted		
Hand position	Right stimulus	t test	Left stimulus	Right stimulus	t test	Left stimulus	Right stimulus	t test	Left stimulus
Right Hand	296.8	2.59*	342.5	322.4	3.09*	363.6	307.7	3.07**	358.8
Left hand	333.4	3.51**	294.8	360.3	3.25*	303.1	334.2	4.00**	321.4

* $p < .05$. ** $p < .01$.

Table 2
Reaction Time (in ms) as a Function of Head Position, Stimulus Position, and Position of Responding Hand: Experiment 2

	Head upright			Head right-tilted			Head left-tilted		
Hand position	Top stimulus	*t* test	Bottom stimulus	Top stimulus	*t* test	Bottom stimulus	Top stimulus	*t* test	Bottom stimulus
Top hand	324.9	2.76*	369.0	347.8	1.55***	330.2	372.5	3.31*	328.1
Bottom hand	364.9	4.18**	324.0	330.0	2.67*	349.8	334.1	2.60*	376.7

* $p < .05$. ** $p < .01$. *** $p > .10$.

cording to a t test ($p < .05$). Conversely, the top (or right) hand was 18 ms faster in responding to the lower (or right) stimulus than to the upper (or left) stimulus. Four subjects out of 6 showed the effect that, however, fell just short of significance in the statistical analysis ($p < .1$).

When the head was tilted to the left, the top (or left) hand was 43 ms faster in responding to the lower (or left) stimulus than to the upper (or right) stimulus, and the bottom (or right) hand was 44 ms faster in responding to the upper (or right) stimulus than to the lower (or left) stimulus. All subjects showed both effects, which were statistically significant at the statistical analysis ($p < .05$).

Discussion of Experiments 1 and 2

The results in the head-upright condition with both the vertical and the horizontal dispositions of the lights conformed to those of several previous similar studies (Anzola et al., 1977; Brebner et al., 1972; Nicoletti & Umiltà, 1983). Compatible reactions involved right–right, left–left, top–top and bottom–bottom S–R pairing and were about 50 ms faster than incompatible reactions involving right–left, left–right, top–bottom, and bottom–top S–R pairings.

The novel finding of these experiments is that quantitatively similar compatibility effects occurred even when the light array was perpendicular to the response keys and the head was tilted 90° to the left or the right. The compatibility effects observed in these conditions can be accounted for in terms of preferential S–R associations, based on the adoption of an environmental frame of reference for coding the stimulus positions and an egocentric frame of reference for coding the positions of the response effectors in Experiment 1 (horizontal light display). Conversely, the results of Experiment 2 (vertical light display) are best attributed to the employment of an egocentric frame of reference for coding the stimulus positions and of an environmental frame of reference for coding the positions of the response effectors. In both cases, the simultaneous application of two different frames of reference to the description of the spatial characteristics of the stimulus and the response array was apt to lead to the prompt identification of a *right* light with a *right* response effector and a *left* light with a *left* response effector. In turn, this coincidence between the stimulus code and the response effector code provided the basis for compatible and incompatible S–R associations.[1]

[1] Another interpretation of these findings has been suggested by G. Rizzolatti and G. Berlucchi (personal communication, February 1983). When the head is tilted 90°, the eyes counter-rotate by about 5°–6°. As a result, the LED in the environmental space corresponding to the direction of head tilt would be brought closer to the right visual field and the left one, to the left field. Perhaps the subject used this retinal position as a way of coding the lights, and this, in turn, gave rise to the compatibility effects we observed. We think this is unlikely. None of the subjects reported, and, as far as we know, none was aware of the position of the LEDs relative to the retinal vertical. In fact, if anything, it is likely that they may have coded the lights in the opposite direction. Berlucchi has called our attention to the Aubert phenomenon (see Howard, 1982, p. 427), which accompanies ocular counter-rotation. A horizontal line and, we assume, the imaginary line joining the two lights appears to rotate counter to the head tilt, that is, in the same direction as the counter-rotation of the eyes. Perceptually, this effect is opposite to the physical one affecting retinal position. Because the Aubert phenomenon reflects the subject's perceptual awareness of the position of the lights, it is much more likely that perceived location rather than retinal location determines the left-right code assigned to the lights.

The term *response effector,* as used in the present discussion, confounds two elements: the key and the responding hand. In previous experiments performed with the head in a normal upright position and with both the stimulus array and the response array disposed horizontally, we found that the factor that facilitates the response in the compatible situation is the correspondence between the side of the stimulus and the side of the response key rather than the correspondence between the side of the stimulus and the responding hand. In other words, the right key was faster for the right stimulus, and the left key was faster for the left stimulus, regardless of whether the right key was pressed with the right hand and the left key was pressed with the left hand (uncrossed condition) or the right key pressed with the left hand and the left key pressed with the right hand (crossed condition; Anzola et al., 1977; Brebner et al., 1972; Nicoletti et al., 1982; Simon, Hinrichs, & Craft, 1970; Wallace, 1971). To determine whether the compatibility effects observed in Experiments 1 and 2 were due to a light/key compatibility or to a light/hand compatibility, subjects crossed their hands in Experiments 3 and 4, and their performance was compared to the hands uncrossed conditions in Experiments 1 and 2.

Experiments 3 and 4

In Experiment 3 the light array was horizontal, and the subject was tested with the head tilted 90° to the right and to the left as in Experiment 1, except that the hands were crossed. The right hand, located on the left side of the head, pressed the key above it, and the left hand, located on the right side of the head, pressed the key below it. The hand positions were reversed after the head was tilted to the left (see Figures 1e and 1f). The head-upright condition was run with the hands uncrossed and served as a control for the presence of the typical S–R compatibility effects.

In Experiment 4 the light array was vertical, and when the head was tilted to the right, the left hand was on the top of the head and pressed the key located to the right of the head, and the right hand was on the bottom of the head and under the chin and pressed the key located to the left of the head. That is, hand positions were crossed with respect to those shown in Figures 1c and 1d. The hands were thus aligned horizontally. The hand positions were reversed when the head was tilted to the left. In this experiment there was also a control session with the head in the upright position and the hands uncrossed.

The hands uncrossed in the head-upright condition was the standard against which other conditions were compared in terms of the magnitude and nature of the compatibility effect. The most interesting comparisons in this study, however, were between the crossed-hands conditions in Experiments 3 and 4 with those of the uncrossed conditions in Experiments 1 and 2. It is well known from extensive published research that crossing the hands with the head upright leads to a compatibility effect that is determined by hand location relative to stimulus location rather than by responding hand as such. Because hand location and stimulus location are orthogonal dimensions in the head tilt condition, it is important to determine what effect, if any, crossing the hands has on spatial S–R compatibility.

Method

Six subjects as in Experiments 1 and 2 served in the present experiments. The apparatus and the procedures, except for the crossing of the hands, were the same as in Experiments 1 and 2; more precisely, under conditions of head rotation Experiment 3 was the crossed-hands counterpart of Experiment 1, and Experiment 4 was the crossed-hands counterpart of Experiment 2.

Results and Discussion

Tables 3 and 4 show mean RT as a function of head position, stimulus position, and responding hand. It is clear from the table that the results of Experiment 3 replicate those of Experiment 1 in that the right hand was faster in responding to the right stimulus in environmental space, and the left hand was faster in responding to the left stimulus, regardless of head position. Similarly, the results of Experiment 4 replicate those of Experiment 2. In the head upright position, the top hand was faster with the top light, and the bottom hand was faster with the bottom key; whereas in both conditions of head rotations, the right hand was faster with the light in the right egocentric space, and the left hand was faster with the light in the left egocentric space.

Table 3
Reaction Time (in ms) as a Function of Head Position, Stimulus Position, and Responding Hand: Experiment 3

Hand position	Head upright			Head right-tilted			Head left-tilted		
	Right stimulus	*t* test	Left stimulus	Right stimulus	*t* test	Left stimulus	Right stimulus	*t* test	Left stimulus
Right hand	297.1	3.49**	347.3	325.4	2.72*	372.8	334.5	3.78**	373.5
Left hand	341.5	12.7***	312.6	374.2	2.70*	342.3	371.3	2.60*	346.8

* $p < .05$. ** $p < .01$. *** $p < .001$.

Analysis of variance carried out on the results of Experiment 3 with head position (upright, right-tilted, left-tilted), stimulus position (right and left in the environmental space), and responding hand (right and left) as factors showed a significant effect of the interaction between stimulus position and responding hand, $F(1, 5) = 12.4$, $p < .05$, that did not depend on head position. The three-factor interaction was not significant. The latter finding obviously reflects the fact that with all head positions the right hand was faster for the environmental right stimulus, and the left hand was faster for the environmental left stimulus. Right–right and left–left stimulus–hand pairings were significantly faster than right–left and left–right stimulus–hand pairings both in the head-upright condition and in the right- or left-tilt conditions, as shown by *t* test for matched scores (see Table 3).

Further, for both the right-tilted condition and the left-tilted condition the differences between the scores for the compatible reactions and those for the incompatible reactions were compared with the corresponding differences observed under the same conditions of head rotation in Experiment 1. Two *t* tests for unpaired scores showed that in both the right-tilted condition and the left-tilted condition there was no significant difference between the advantage for compatible over incompatible reaction in Experiment 3 and that in Experiment 1 ($p < .1$).

An analysis of variance carried out on the results of Experiment 4 with head position (upright, right-tilted, left-tilted), stimulus position (up and down in the environmental space), and position of responding hand (top and bottom in egocentric space) produced a significant Stimulus Position × Responding Hand interaction, $F(1, 5) = 21.2$, $p < .006$, due to the fact that in all head-position conditions the hand that was up (in the environmental or egocentric space, depending on whether the head was upright or tilted) was faster for the top light, and the hand that was on the bottom in the environmental or egocentric space was faster for the bottom light. To take into consideration the difference in hand position relative to Experiment 2, the data can be described in another way. In the right-tilt condition, the hand that was on top in egocentric space was the left hand, and its preferred stimulus was also in the left ego-

Table 4
Reaction Time (in ms) as a Function of the Head Position, Stimulus Position, and Responding Hand: Experiment 4

Hand position	Head upright			Head right-tilted			Head left-tilted		
	Top stimulus	*t* test	Bottom stimulus	Top stimulus	*t* test	Bottom stimulus	Top stimulus	*t* test	Bottom stimulus
Top hand	308.8	6.0**	328.7	367.3	1.41***	352.8	336.2	2.77*	364.2
Bottom hand	325.7	2.60*	303.5	359.9	1.88***	342.7	352.9	2.74**	318.0

* $p < .05$. ** $p < .01$. *** $p > .10$.

centric space; the hand that was on the bottom in egocentric space was the right hand, and its preferred stimulus was in the right egocentric space. The three-factor interaction was also significant, $F(2, 10) = 5.9, p < .02$, because the difference between stimulus–hand pairings, although in the same direction in all three head-positions, was considerably smaller in the right-tilt condition than in the other two. The up-up and down-down S–R pairings were significantly faster than the corresponding up-down and down-up S–R pairings in the head-upright condition and in the left-tilt condition, but not in the right-tilt condition. The explanation for this difference is not readily available but may be sought in differential relations between the dominant and nondominant hands on one side and the up–down dichotomy on the other (see Ladavas, 1983a). Ladavas found that when the lights are aligned vertically and the hands horizontally, the dominant hand, be it right or left, responds more quickly to the top than to the bottom light and vice versa for the nondominant hand. Additional significant factors were head position, $F(2, 10) = 4.3, p < .04$, with the head upright condition yielding faster RTs than the other, and the side of stimulus, $F(1, 5) = 8.4, p < .03$. These effects are irrelevant to the conclusions of the experiment and will not be discussed further.

Two *t* tests for unpaired scores showed that the advantage of compatible over incompatible reactions under the two conditions of head rotation in Experiment 4 was not significantly different from the corresponding advantages for compatible over incompatible reactions in the two same conditions of head rotation in Experiment 2. This again points to response hand per se rather than hand position as the factor determining S–R compatibility effects when the head is rotated.

In conclusion, Experiments 3 and 4 indicate that the pattern of S–R compatibility effects observed with the head rotated in Experiments 1 and 2 is most simply explained by an association between the right hand and the stimulus that can be classified as right, whether in environmental or egocentric space, and between the left hand and the stimulus that can be classified as left. It appears that under conditions of head rotation it is the side of the responding hand rather than response position that determines the set of rules for the differential S–R associations underlying the spatial compatibility effects. In this respect, the results are contrary to those found in the head-upright condition (Anzola et al., 1977; Brebner et al., 1972; Wallace, 1971), where it is the hand position, rather than the hand per se, that determines the compatible and incompatible S–R couplings.

General Discussion

The most significant and surprising finding in light of current theories of spatial S–R compatibility effects is the existence of compatibility effects even when the spatial coordinates of stimuli and responses are perpendicular (or orthogonal) to each other. Current attempts at interpreting spatial S–R compatibility effects have ranged from the simple assumption of a natural stereotypic tendency to react toward the source of the stimulus (Simon, 1969) to the adoption of a complex system of comparisons between the visually encoded position of the stimulus and the proprioceptively felt position of the responding body part (Wallace, 1971). Although these interpretations have been successful in explaining some of the reported spatial compatibility effects, they are unable to account for the effects of factors such as stimulus salience and markedness (Cotton, Tzeng, & Hardyck, 1980) and preference for given directions of movement of different body parts (Bauer & Miller, 1982). The results reported here add to the complexity of the picture by underlining the importance of two further variables, the differentiation between the right and the left hand, independent of their position, and the ability to use different frames of reference for categorizing the position of the visual stimuli.

Previous experiments on S–R compatibility have emphasized the importance of response position relative to the stimulus, rather than that of responding hand (Brebner et al., 1972; Wallace, 1971). The present results indicate that at least under conditions of head rotation, spatial compatibility effects are based on a right–left classification of the responding hand. More precisely, it is submitted that the coding of the responding hand as right or left, independent of its position relative to both the stimuli and the head, was responsible for the selection of an appropriate frame of reference, whether environmental or egocentric, and for classifying the stimuli as right and left. Although it is known that under conditions of head rotation normal people tend to use the environmental rather than egocentric frame of reference for encoding visual stimuli (Attneave & Olson, 1967; Attneave & Reid, 1968), it is also clear that a shift to the egocentric frame of reference can promptly occur under voluntary or external control (Attneave & Reid, 1968). It appears that in the present experiments subjects selected the environmental frame of reference when the stimulus display was horizontal and the egocentric frame of reference when the stimulus display was vertical, thereby arriving in both cases at a right–left distinction of the stimuli that allowed a matching with the right–left classification of the responding hand.

The conclusion that S–R compatibility effects observed under head rotation are of a spatial nature can be accepted only if one excludes the possible mediating action of the verbal tags "right" and "left" in the formation of the preferred S–R pairings. If a subject says to himself or herself the word *left* upon the appearance of the left stimulus, this may facilitate the response with the left hand and hinder that with the right hand. This "verbal mediation" hypothesis is quite unlikely on two counts. First, it is known that the verbal classification of locations along the right–left axis is considerably more difficult than the verbal classification of locations along the up–down axis (Maki, Grandy, & Hauge, 1979; Sholl & Egeth, 1981). If subjects had employed a verbal strategy for matching stimuli and responses, it seems reasonable that they ought to have chosen an up–down rather than right–left classification. Second, spatial S–R compatibility effects comparable to those shown by normal adults are present in children who have not yet learned to tell right from left and therefore cannot use verbal labels to encode the positions of stimuli and responses (Ladavas, 1983b).

Our results, as well as those from other studies, suggest that individuals have a preferred tendency to respond to given sources of stimulation no matter what the relation between stimuli and responses. The tendencies that predominate depend on the conditions that obtain. When egocentric and environmental frames of reference coincide, and stimuli and responses are distributed along the same plane, then the relative position of stimuli and responses with respect to each other determines S–R compatibility effects. If the stimuli and responses are perpendicular to each other and the frames of reference do not coincide, responding hand replaces response position as the relevant factor. Consequently, this introduces a tendency to code stimulus position in terms of left and right. Subjects will adopt that frame of reference that enables them to do so and to map the stimuli easily onto the corresponding hand. When none of these factors can operate, such as when the subject responds with only one limb, then other factors such as movement sequences within that limb will determine S–R compatibility effects. A general model of S–R compatibility effects will have to be sensitive to these contingencies.

In conclusion, the present study indicates that under conditions of head rotation and with stimulus and response arrays perpendicular to each other, normal people tend to form differential S–R associations that fall within the category of spatial compatibility and incompatibility effects. These effects are possible because of a conjoint action of the right–left specification of the responding hand and the flexible employment of a dual frame of reference, which allows a right–left classification of the stimuli independent of whether they are horizontally or vertically disposed.

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