Right-left prevalence effect with horizontal and vertical effectors

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We investigated the right-left prevalence effect in spatial compatibility tasks by assessing subjects' performance on a two-dimensional task in which both the horizontal and vertical spatial dimensions were task relevant. Two experiments were performed, in which stimulus-response mappings were one-dimensional (Experiment 1) and two-dimensional (Experiment 2). The subjects responded by using either horizontal or vertical effectors to stimuli appearing in four possible locations. With the one-dimensional mapping, the spatial compatibility effect was present only in the dimension relevant to the mapping. With the two-dimensional mapping, the horizontal compatibility effect was always present, whereas the vertical compatibility effect was present only when vertical effectors were used. This pattern of results indicates that horizontal coding takes place with either horizontal or vertical effectors, whereas vertical coding takes place only when vertical effectors are used.

Performance is better on tasks with a compatible stimulus-response (S-R) mapping than on those with an incompatible S-R mapping (for reviews, see Hommel & Prinz, 1997, and Proctor & Reeve, 1990). For instance, in a spatial S-R compatibility task the relevant dimension is the stimulus position (e.g., left or right), and the response consists in pressing one of two buttons (e.g., that to the left or that to the right). It has been repeatedly shown that, of the two possible S-R mappings, the compatible mapping results in better performance in terms of speed and accuracy than the incompatible one does. This advantage for the compatible with respect to the incompatible mapping has been called the *spatial compatibility effect*. The spatial compatibility effect also occurs when stimulus and response locations are arranged in vertical positions (see, e.g., Nicoletti & Umiltà, 1984)—that is, performance is better on vertically compatible trials than on vertically incompatible trials.

When S-R mappings vary along both the horizontal and vertical dimensions (i.e., in a two-dimensional task), often the spatial compatibility effect is greater for one dimension. In a series of works (Nicoletti & Umiltà, 1984, 1985; Nicoletti, Umiltà, Tressoldi, & Marzi, 1988), it was noted that in such two-dimensional tasks the spatial compatibility effect was always greater for the horizontal dimension. In Nicoletti and Umiltà's (1984, Experiment 4; 1985, Experiment 1) studies, subjects were required to respond to diagonally placed stimuli with the two hands positioned at different heights (diagonal response locations). The two mappings (i.e., horizontal and vertical) were varied orthogonally, thus producing horizontally and/or vertically compatible or incompatible trials. Despite the fact that the subjects were instructed exclusively in terms of top and bottom locations, the spatial compatibility effect for the horizontal dimension (*horizontal effect*, or HE) was considerably greater than that for the vertical dimension (*vertical effect*, or VE). The experiment was replicated with the use of one hand and the contralateral foot, which were considered to be more natural vertical effectors than two hands (Nicoletti & Umiltà, 1985, Experiment 3). A normal HE was found, whereas the VE was null. Nicoletti & Umiltà (1984, 1985; Nicoletti et al., 1988) concluded that there is a sort of right-left over top-bottom prevalence in the generation of spatial codes and called this phenomenon the *right-left prevalence effect*.

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Hommel (1996) challenged this conclusion by providing evidence that instruction bias (Experiment 1) and effector bias (Experiment 2) were responsible for the right–left prevalence effect. He hypothesized that in Nicoletti and Umiltà's (1984, 1985; Nicoletti et al., 1988) experiments, subjects actually followed horizontal instructions despite being explicitly given vertical instructions only. Because Nicoletti and Umiltà (1984, 1985; Nicoletti et al., 1988) had conducted both experiments with one-dimensional horizontal and vertical conditions and experiments with two-dimensional conditions, Hommel noted that, by comparing reaction times (RTs) in the two types of one-dimensional conditions, one could estimate that horizontal codes were available 49–145 msec before vertical ones. Therefore, it is reasonable to suppose that in two-dimensional conditions, in which responses could be based on either horizontal or vertical codes, subjects would make use of the faster, horizontal codes rather than the slower vertical codes. In accordance with this possibility, RTs for the two-dimensional conditions resembled those of the horizontal one-dimensional conditions, not those of the vertical one-dimensional conditions.

In Experiment 1, Hommel (1996) replicated Nicoletti and Umiltà's (1984, 1985; Nicoletti et al., 1988) experimental conditions with bimanual responses, instructing half of the subjects in terms of the vertical dimension as in Nicoletti and Umiltà's (1984, 1985) and Nicoletti et al.'s (1988) experiments, and half in terms of the horizontal dimension. The results showed that RTs were shorter overall with vertical instructions than with horizontal instructions. More important, with vertical instructions, both a VE and an HE were found, the VE being greater than the HE. In contrast, with horizontal instructions only a significant HE was found. As Hommel noted, this pattern of results might still be taken as evidence that right–left codes are stronger than top–bottom ones. A possible explanation of the right–left prevalence might invoke the use of right–left effectors for responding. Hommel reasoned that using two hands or one hand and the contralateral foot to execute the top and bottom responses introduces a response bias toward the horizontal dimension, which might explain why the right–left prevalence effect arose in his and in Nicoletti and Umiltà's (1984, 1985; Nicoletti et al., 1988) works.

In his Experiment 2, Hommel (1996) employed a task identical to that in Experiment 1 but avoided the use of the right–left response effectors by requiring subjects to use only one hand to move the lever of a joystick. Results showed no prevalence of right–left over top–bottom codes (see also Vu & Proctor, 2001). For both instruction conditions, there were both an HE and a VE. Under horizontal instruction conditions, the HE was greater, whereas under the vertical instruction conditions the VE was greater. Hommel's conclusion was that there is no right–left over top–bottom prevalence in the generation of spatial codes. Therefore, he proposed a *response bias*

account, which stated that the right–left prevalence is an artifact due to the use of right–left effectors.

A series of recent works (Vu & Proctor, 2001, 2002; Vu, Proctor, & Pick, 2000) has provided empirical evidence that right–left prevalence arises when the S–R environment enhances the horizontal dimension (an explanation known as the *relative salience account*). The basic idea of the relative salience account is that the coding of stimulus and response locations occurs relative to their more salient dimension (see, e.g., Proctor & Reeve, 1985), and performance is more efficient when the salient dimensions of stimuli and responses correspond than when they do not. In this view, right–left prevalence would occur when the horizontal dimension is made more salient than the vertical dimension. Vu and Proctor (2001) showed that the salience of the horizontal dimension is enhanced by the use of two right–left effectors instead of a single effector (which, of course, is exactly what Hommel, 1996, had proposed) or by positioning right–left effectors in a manner that renders them more distinct (e.g., more distant from each other; Vu & Proctor, 2001; Vu et al., 2000). In accordance with the *salient features coding* interpretation, Vu and Proctor (2002) also found that right–left prevalence arises when the salience of the stimulus display was biased in favor of the horizontal dimension by positioning the two stimulus locations at the two opposite corners of an imaginary rectangle. The relative salience account predicts that if the salience of the vertical dimension is enhanced, top–bottom prevalence should arise. Accordingly, Vu and Proctor (2001, 2002) showed that when stimuli and/or responses render salient the vertical dimension, the spatial compatibility effect is greater for the vertical dimension. For example, using ipsilateral hand and foot for responding enhanced the vertical dimension, thus generating top–bottom prevalence.

Vu and Proctor (2001) proposed their relative salience account as an alternative to the response bias account (Hommel, 1996), because they showed that the use of right and left effectors is not sufficient in generating right–left prevalence. Indeed, they did not obtain right–left prevalence when subjects responded with two fingers of the same hand. In contrast, it seems to us that the response bias and relative salience accounts are not alternative but, rather, that the latter is a more comprehensive variant of the former. The response bias account suggests that the right–left prevalence effect is produced by the use of responses that are coded as left or right. The relative salience account goes further and claims that the use of left and right effectors is only one way of manipulating the dimensional salience that produces the right–left prevalence effect. In fact, the salience of the horizontal dimension is also achieved by biasing the stimulus display in favor of the horizontal dimension. Together with these environmental factors, there is one structural, intrinsic property that is relevant: The right–left prevalence effect arises only when response selection is be-

tween two hands or between hand and foot, whereas it does not manifest itself with a single responding hand that either moves a joystick or presses two keys with two fingers. Given these considerations, henceforth we refer to *the relative salience account of the right-left prevalence effect*, which emphasizes both the role of the environmental features of the S-R sets and that of the structural constraint (namely, more than one responding hand) in the occurrence of right-left prevalence.

On the whole, these studies led Vu and Proctor (2001, 2002; Vu et al., 2000) to conclude that both horizontal and vertical codes are formed and processed at stimulus presentation. However, when the code for a single dimension is sufficient to determine the correct response, one spatial dimension may prevail. In the absence of a salient frame of reference provided by the way stimuli and/or responses are arranged, instructions determine which dimension prevails. When the arrangement of stimuli and/or responses enhances a spatial dimension, there is a prevalence of spatial codes originating from that dimension. In other words, when one dimension is more salient than the other, instructions are less influential because spatial coding occurs with respect to the frame of reference for the more salient dimension. Accordingly, the distinction in right-left effectors produces right-left prevalence because it enhances the salience of the horizontal dimension, provided that two hands are used for responding.

Vu and Proctor's (2001, 2002; Vu et al., 2000) reasoning pertains to two-dimensional spatial compatibility in which a single dimension is sufficient to determine the correct response. In contrast, the main purpose of the present study was to investigate two-dimensional spatial compatibility tasks that require the use of codes arising from both the horizontal and the vertical dimensions for determination of the correct response.

The display we used was designed to equate the salience of the horizontal and vertical dimensions, with four stim-

ulus positions located at the corners of an imaginary square. Horizontal or vertical effectors were used for responding, and instructions mapped stimuli onto effectors in one dimension (Experiment 1) or in two dimensions (Experiment 2). On the basis of the relative salience account, a prediction can be drawn: Prevalence effects should arise depending on the effectors used for responding. That is, because the stimulus display was not biased in favor of either dimension, response arrangement should determine which codes are used in selecting the correct response.

As Vu et al. (2000) pointed out, there are two different ways to view the effect of spatial codes on performance, which can be revealed by two different ways of treating the data. The first is to consider the main effects of horizontal and vertical compatibility, which allows one to evaluate the weight of each dimension. The second consists in comparing compatibility effects on four experimental conditions (both dimensions, horizontal dimension only, vertical dimension only, and neither dimension), which makes it possible to evaluate the effect size for the conditions with compatibility on each dimension alone. Therefore, the data of the two experiments reported here were analyzed in both ways.

EXPERIMENT 1

Experiment 1 served primarily as a baseline for the second experiment. This was considered to be necessary because, in the present study, the stimulus appeared in four positions instead of in the two used in all previous works on the prevalence effect (Hommel, 1996; Nicoletti & Umiltà, 1984, 1985; Nicoletti et al., 1988; Vu & Proctor, 2001, 2002; Vu et al., 2000).

In one condition (Experiment 1A), the subjects used their hands and, in different blocks, their feet to respond to the stimulus that appeared in one of four positions (top

Figure 1. Illustration of the S-R mapping rules used in one horizontally compatible block of Experiment 1A (panel A) and in one vertically compatible block of Experiment 2A (panel B).

right, top left, bottom right, and bottom left; see Figure 1A). The instructions mapped two stimulus locations on one effector and were expressed in terms of the horizontal dimension. For example, for compatible blocks, the instructions were: "When the stimulus is on the right, press the right key/pedal; when the stimulus is on the left, press the left key/pedal." The other condition (Experiment 1B) was the same as that used in Experiment 1A, except that the subjects used ipsilateral effectors (hand and foot) to respond (see Figure 1B). The instructions were expressed in terms of the vertical dimension; for example, for compatible blocks, the instructions were: "When the stimulus is at the top, press the top key; when the stimulus is at the bottom, press the bottom pedal."

According to the relative salience account, the use of horizontal (Experiment 1A) and vertical (Experiment 1B) effectors should enhance salience of the horizontal and vertical dimensions, respectively. Therefore, in Experiment 1A right-left prevalence was expected, whereas in Experiment 1B top-bottom prevalence was expected.

Method

Subjects

Sixteen students of the University of Modena and Reggio Emilia served as volunteer subjects. They had normal or corrected-to-normal visual acuity, and they were naive as to the purpose of the experiment. Eight subjects were randomly assigned to Experiment 1A and 8 to Experiment 1B.

Apparatus and Stimuli

The experiment took place in a dimly lit room. The subject sat in front of a computer screen on which the stimulus appeared. The head was positioned in an adjustable head- and chinrest so that the distance between the eyes and the center of the screen was about 60 cm. The stimulus (a circle of 0.8° diameter) appeared in the top-right, top-left, bottom-right, or bottom-left corner of an imaginary square 0.5 cm from the top and bottom edges of the screen. Thus, the stimulus appeared at 9.5° of horizontal and vertical eccentricity from the center of the screen. The PC monitor was located above the PC machine, so that eye level was approximately aligned with the level of the fixation point. In every experimental session, the stimulus randomly appeared in each of the four positions. An acoustic warning signal was provided 300 msec before stimulus onset. The stimulus flashed for 100 msec and was followed by a blank response interval of 1,000 msec. At the end of each trial, feedback about RT and accuracy was provided below the fixation cross, followed by a 1,300-msec intertrial interval.

The top response device (operated by the left and right hands) consisted of two buttons of the MEL response box. One button was located to the left of body midline and was pressed by the left index finger, whereas the other was located to the right and was pressed by the right index finger. The bottom response device (operated by the left and right feet) consisted of two pedals (plugged into the response box), one located to the left and the other to the right of body midline. The horizontal distance was 9 cm between hands and about 40 cm between feet. The vertical distance between ipsilateral top and bottom response devices was about 70 cm. Two effectors at a time were used for responding, depending on experimental condition (i.e., A or B) and instructions.

Procedure

Experiment 1A. Each subject performed four experimental conditions in four blocks (A, B, C, and D) of 60 trials each. Every

block was preceded by 20 practice trials. In the horizontally compatible blocks (A and B), the subjects responded to top-right and bottom-right stimuli with the right effector and to top-left and bottom-left stimuli with the left effector. Block A was performed with the hands; therefore, the top stimulus positions were vertically compatible, whereas the bottom stimulus positions were vertically incompatible. Block B was performed with the feet, and so the bottom stimuli were vertically compatible, whereas the top stimuli were vertically incompatible.

In the horizontally incompatible blocks (C and D), the top-right and bottom-right stimuli were paired with the left effector and the top-left and bottom-left stimuli with the right effector (i.e., hands in Block C and feet in Block D). Of course, vertical compatibility for Blocks C and D was exactly the same as for Blocks A and B, respectively. Each trial was thus defined in terms of horizontally and/or vertically compatible or incompatible S-R pairings. The order of blocks was counterbalanced across subjects, with the constraint that the two compatible blocks followed the two incompatible blocks or vice versa.

The instructions stressed both speed and accuracy and described stimuli and effectors exclusively in terms of right and left, as in the following example: "When the stimulus is on the right, press the right key/pedal; when the stimulus is on the left, press the left key/pedal."

Experiment 1B. The procedure was the same as in Experiment 1A, except as follows. In the vertically compatible blocks (A and B), the subjects responded to top-right and top-left stimuli with the hand and to bottom-right and bottom-left stimuli with the foot. Block A was performed with the right effectors: The top and bottom right stimuli were horizontally compatible, whereas the top and bottom left stimuli were horizontally incompatible. Block B was performed with the left effectors: The top and bottom left stimuli were horizontally compatible, whereas the top and bottom right stimuli were horizontally incompatible. In the vertically incompatible blocks (C and D), the top-right and top-left stimuli were paired with the foot, whereas the bottom-right and bottom-left stimuli were paired with the hand. Block C was performed with the right effectors, whereas Block D was performed with the left effectors: Horizontal compatibility in Block C and Block D was computed as in Block A and in Block B, respectively. The instructions defined stimuli and effectors only in terms of the vertical dimension; for example, for the compatible blocks, the instructions were: "When the stimulus is at the top, press the top key; when the stimulus is at the bottom, press the bottom pedal."

RESULTS

Only RTs in the 100- to 900-msec range were considered for subsequent analyses. This yielded a 1.3% rate of outliers, consisting of 0.9% RTs shorter than 100 msec and 0.4% RTs longer than 900 msec. In addition, 4.9% of the trials were error trials. Two omnibus analyses of variance (ANOVAs) were performed on errors and RTs, with condition (A vs. B) considered as a between-subjects factor and horizontal dimension (compatible vs. incompatible) and vertical dimension (compatible vs. incompatible) considered as within-subjects factors. In the error analysis, the interactions between condition and horizontal dimension and between condition and vertical dimension were significant [$F(1,14) = 6.34, p = .025$, and $F(1,14) = 5.45, p = .035$, respectively]. Pairwise comparisons showed that in Experiment 1A there were fewer errors on horizontally compatible trials (1.8%) than on horizontally incompatible trials (3.9%). Similarly, in Experiment 1B, vertically compatible trials produced fewer

errors (1.9%) than did vertically incompatible trials (3.9%).

The RT analysis showed that the subjects in Experiment 1A were 46 msec faster than those in Experiment 1B [293 vs. 347 msec; $F(1,14) = 5.45, p = .035$]. The effect of horizontal compatibility was significant [$F(1,14) = 16.13, p < .001$], as was the effect of vertical compatibility [$F(1,14) = 8.99, p = .01$]. These effects were modified by the interactions with condition [$F(1,14) = 25.41, p < .001$ for HE, and $F(1,14) = 10.43, p = .006$ for VE]. In particular, there was a significant HE in Experiment 1A but not in Experiment 1B [49 vs. -3 msec; $F(1,7) = 25.93, p < .001$] and a significant VE in Experiment 1B but not in Experiment 1A [64 vs. -6 msec; $F(1,7) = 11.63, p = .02$; see Table 1 for a summary of the compatibility effects obtained in each condition of each experiment].

Other ANOVAs were conducted independently for Experiments 1A and 1B, with condition (compatibility effect on both dimensions, on the horizontal dimension only, on the vertical dimension only, or on neither dimension) considered as the only within-subjects factor.

In both ANOVAs, condition was significant [$F(1,3) = 6.69, p = .03$ for Experiment 1A, and $F(1,3) = 5.02, p = .03$ for Experiment 1B]. The pairwise comparisons for Experiment 1A showed that RTs in the condition with horizontal compatibility alone (268 msec) were as short as those in the condition with both types of compatibility (269 msec), whereas RTs in the condition with vertical compatibility alone (319 msec) were as long as those in the condition with neither compatibility (315 msec). All other pairwise comparisons were significant ($p \leq .003$). For Experiment 1B, an opposite trend was obtained. In particular, the RTs in the vertical-compatibility-alone condition (315 msec) and those in the condition with both types of compatibility (315 msec) were equally short, and the RTs in the horizontal-compatibility-alone condition (384 msec) did not differ from those in the neither-compatibility condition (374 msec). All other pairwise comparisons were significant ($p \leq .02$).

DISCUSSION

The results of Experiment 1 are clear-cut. Both compatibility effects arose even if four (instead of two) stimulus

positions were used. More important, when the instructions paired stimuli and effectors in a single dimension (i.e., horizontal or vertical), spatial compatibility was shown for that dimension only. This is well documented by the absence of VE in Experiment 1A and the absence of HE in Experiment 1B. That only one code affected performance is supported by the fact that in Experiment 1A RTs in the horizontal-compatibility-alone condition were equal to those in the condition with both types of compatibility, and RTs in the vertical-compatibility-alone condition were equal to those in the neither-compatibility condition. In contrast, in Experiment 1B the opposite pattern was observed. Thus, when effectors are defined in one dimension and instructions refer to the same dimension, there is no effect of the "irrelevant" spatial dimension that defines stimulus location. Moreover, as is predicted by the relative salience account, response arrangement determines which dimension prevails.

The fact that the subjects in Experiment 1B were slower than those in Experiment 1A deserves attention. The slowness in responding with vertical effectors might be attributed to the need to choose between different types of effectors. In effect, in Experiment 1A responses were made with hands or feet, whereas in Experiment 1B responses were made with hand and foot. However, this explanation does not seem tenable given that RTs in the vertical condition were longer even when the vertical effectors were the two hands positioned at different heights (see Hommel, 1996).

Another possibility might be that the vertical code is formed more slowly than the horizontal code, and so an overall slowing of the response is generated. Together with relative salience, the time needed for the generation of spatial codes might be one of the reasons for which the right-left prevalence effect arises (Hommel, 1996). A post hoc RT bin distributional analysis was performed using the Vincentization procedure introduced by Ratcliff (1979; also see Rubichi, Nicoletti, Iani, & Umiltà, 1997). In particular, we calculated the mean RTs for the first through the fifth bins of the rank-ordered raw data (each bin contained 20% of the data) separately for Experiments 1A and 1B and for compatible and incompatible trials (horizontal and vertical compatibility for Experiments 1A and 1B, respectively). This procedure provides a measure over time of the magnitude of the spatial compatibility effect through a calculation of the bin-by-bin difference between the mean RTs of incompatible and compatible trials. An ANOVA was performed, with compatibility and bin considered as within-subjects factors and condition as a between-subjects factor. All of the main effects were significant ($F_s > 5.45, p_s < .04$), as were the two-way interactions of compatibility $\times$ bin and condition $\times$ bin ($F_s > 11.10, p_s < .001$). These effects were modified by the three-way interaction of condition $\times$ compatibility $\times$ bin [$F(4,56) = 6.92, p < .001$; see Figure 2].

The HEs were of 37, 48, 52, 53, and 53 msec, and the VEs were of 34, 39, 55, 76, 120 msec from the first to the

Table 1
Mean RTs (in Milliseconds) for Compatible and Incompatible Trials and Effect Size for Each Dimension in the Three Experiments

Trial	Experiment							
	1A		1B		2A		2B	
	HE	VE	HE	VE	HE	VE	HE	VE
C	268	294	350	315	352	368	357	357
I	317	291	344	379	387	371	376	376
I - C	49	-3	-6	64	35	3	19	19

Note—HE, horizontal effect; VE, vertical effect; C, compatible; I, incompatible; I - C, effect size (incompatible minus compatible).

Figure 2. Mean reaction times (RTs) for compatible (C) and incompatible (I) trials for each bin of the HE (Experiment 1A) and of the VE (Experiment 1B).

fifth bins, respectively. The pattern of the relevant results obtained with the pairwise comparisons showed a tendency toward significance of the difference between the two effects at the fifth bin ($p = .08$). In addition, the mean RTs of the two experimental conditions were different for the slowest bins. In particular, the mean RTs were not significantly different at the first and second bins, tended toward significance at the third bin (283 vs. 330 msec for Experiments 1A and 1B, respectively; $p = .058$), and differed significantly at the fourth (316 vs. 384 msec for the Experiments 1A and 1B, respectively) and fifth (396 vs. 515 msec for Experiments 1A and 1B, respectively) bins ($p = .02$). On the whole, these results clearly indicate that the spatial compatibility effect has different temporal characteristics in the horizontal and vertical dimensions. In particular, the VE seems to increase as RT increases, whereas the HE is constant (see the General Discussion section).

EXPERIMENT 2

The goal of the present experiment was to test performance in two-dimensional spatial compatibility when both spatial dimensions must be used to determine the correct response. As in the previous experiment, there were four stimulus locations and two horizontal or vertical effectors. The instructions paired stimuli and effectors with orthogonal mapping rules. In particular, in Experiment 2A the subjects responded to vertical stimuli with horizontal effectors, whereas in Experiment 2B vertical effectors were mapped to horizontal stimuli (see Figure 3). Thus, the difference between the present experiment and Experiment 1 was that here both spatial dimensions were used in S–R mapping rules, and thus were necessary for determining the correct response.

As we said before, the relative salience account (Vu & Proctor, 2001, 2002; Vu et al., 2000) was put forward to

account for performance on two-dimensional spatial compatibility tasks in which one dimension was sufficient for selection of the correct response. However, predictions can be made also when the codes from both dimensions are task relevant. Of course, the prediction is that the dimension that is salient should prevail—that is, a greater spatial compatibility effect should arise for the dimension in which effectors are coded (horizontal and vertical for Experiments 2A and 2B, respectively).

Method

Subjects. Thirty-two students of the University of Modena and Reggio Emilia, selected as were those in the previous experiment, participated in this experiment. None had participated in the first experiment. Sixteen were randomly assigned to Experiment 2A, whereas the other 16 were assigned to Experiment 2B.

Apparatus, Display, and Procedure. The apparatus and display were as in the previous experiment except as follows. In Experiment 2A (horizontal effector condition), the subjects responded to top-right and top-left stimuli with the right effector and to bottom-right and bottom-left stimuli with the left effector. With regard to the horizontal dimension, top-right and bottom-left stimuli were compatible, whereas top-left and bottom-right stimuli were incompatible. There were four blocks of trials: In Block A, which was performed with the hands, the top stimuli were vertically compatible and the bottom stimuli were vertically incompatible. In Block B, which was performed with the feet, the bottom stimuli were vertically compatible, whereas the top stimuli were vertically incompatible. In Blocks C and D, the right effector was paired with the bottom-right and bottom-left stimuli, whereas the left effector was paired with the top-right and top-left stimuli. The bottom-right and top-left stimuli were horizontally compatible, whereas the top-right and bottom-left stimuli were horizontally incompatible. In Block C the subjects used their hands, and in Block D they used their feet. Of course, vertically compatible and incompatible S–R mappings for Blocks C and D were the same as those described for Blocks A and B, respectively. Each stimulus could thus be defined in terms of horizontally and vertically compatible or incompatible S–R pairings.

In Blocks A and B of Experiment 2B (vertical effector condition), the hand was paired with the top-right and bottom-right stimuli, whereas the foot was paired with the top-left and bottom-left stimuli (right effectors in Block A and left effectors in Block B). In Blocks C and D, the hand responded to the top-left and bottom-left stimuli, whereas the foot responded to the top-right and bottom-right stimuli (right and left effectors in Blocks B and C, respectively). Horizontal and vertical compatibility for each block was calculated by applying the procedure described for Experiment 2A.

Results

Only RTs in the same range as for Experiment 1 were considered. RTs shorter than 100 msec were 0.7%, whereas those longer than 900 msec were 0.6%. Errors were 5.1%.

The same analyses were performed on the present data as on the data in Experiment 1. The error analysis did not yield any significant effect. In the omnibus ANOVA for RTs, the two main effects of HE [$F(1,30) = 15.74, p < .001$] and VE [$F(1,30) = 10.88, p = .003$] and the interaction between VE and condition [$F(1,30) = 5.94, p = .02$] were significant. The interaction between condition and HE was not significant ($p = .238$). Planned comparisons showed that VE was significant in Experiment 2B ($p < .001$) but not in Experiment 2A (19 and

Figure 3. Illustration of the stimulus-response mapping rules used in one block of Experiment 2A (panel A) and in one block of Experiment 2B (panel B). Each stimulus location has been labeled as compatible on both dimensions (B), neither dimension (N), only the horizontal dimension (H), or only the vertical dimension (V), considering the case of the use of two hands (panel A) and the two right effectors (panel B) for responding.

3 msec, respectively; see Table 1), whereas HE was significant for both Experiments 2A and 2B (35 and 19 msec, respectively).

The results of the analysis with one within-subjects factor were significant for both Experiment 2A [$F(3,13) = 9.23, p = .018$] and Experiment 2B [$F(3,13) = 9.62, p < .001$]. In Experiment 2A, RTs in the horizontal-compatibility-only condition were as short (353 msec) as those in the condition with both compatibilities (351 msec), whereas RTs in the vertical-compatibility-only condition were as long (386 msec) as those in the neither-compatibility condition (389 msec). All other pairwise comparisons were significant ($p \leq .01$). In Experiment 2B, RTs in the horizontal-compatibility-only (369 msec) and the vertical-compatibility-only (369 msec) conditions were both longer than those in the condition with both compatibilities (345 msec) and shorter than those in the neither-compatibility condition (383 msec; $p = .04$). In addition, RTs in the conditions with both compatibilities and with neither compatibility differed significantly ($p < .001$).

Given that in Experiment 1 HE and VE had shown different temporal dynamics, we performed an additional ANOVA on the data from Experiment 2B, with dimension (horizontal vs. vertical) and bin as factors. The dimension $\times$ bin interaction was far from significance ($p = .976$).

Discussion

The present experiment was designed to investigate performance in a two-dimensional spatial compatibility task in which both the horizontal and the vertical dimensions have to be processed in order for the correct response to be selected. Orthogonal S-R mapping rules were used to map vertically defined stimulus locations to horizontal effectors (Experiment 2A) or horizontally defined stimulus locations to vertical effectors (Experiment 2B).

Clearly, the results indicate that response manipulation is effective in determining dimensional salience. However, there were important differences with respect to Experiment 1. As was the case for one relevant dimension, when horizontal effectors were used, the horizontal dimension was more salient, generating right-left prevalence. Indeed, in Experiment 2A only the HE manifested itself, whereas there was no sign that the vertical dimension affected performance. On the contrary, when vertical effectors were used, top-bottom prevalence did not arise, VE and HE being of the same magnitude. In addition, RTs in the vertical-alone and horizontal-alone conditions were equivalent and were slower than those in the both-compatibilities condition. In other words, right-left codes always affected performance, whereas top-bottom codes affected performance only when vertical effectors were used. This pattern of results indicates that the right-left prevalence effect when two dimensions are relevant does not depend on the environmental salience of the S-R sets alone (see the General Discussion).

With regard to the temporal dynamics of spatial code formation, when both dimensions are relevant there is no indication of different temporal dynamics in the generation of horizontal and vertical codes. As was indicated by the bin distributional analysis, there were no signs of differences between HE and VE in relation to the speed of response (see the General Discussion).

GENERAL DISCUSSION

In two-dimensional spatial compatibility, S-R sets vary along the horizontal and the vertical dimensions simultaneously. In earlier studies (Nicoletti & Umiltà, 1984, 1985; Nicoletti et al., 1988), it was found that the horizontal dimension was dominant over the vertical dimension.

sion (right–left prevalence effect). Hommel (1996) showed that the distinction of responses in right and left effectors played a role in producing this phenomenon (the response bias account). Vu and Proctor (2001, 2002; Vu et al., 2000) proposed a more comprehensive explanation of the right–left prevalence effect that invokes the salience of the S–R environment (the relative salience account). The right–left prevalence would arise when stimulus and/or response sets enhance the salience of the horizontal dimension. Conversely, if the salience of the vertical dimension is enhanced, top–bottom prevalence should occur. On the whole, these studies show that codes originating from both dimensions are formed and processed; however, certain codes can prevail depending on the relative salience of the horizontal and vertical dimensions.

In the present study, we were interested in assessing performance in two-dimensional situations in which both dimensions have to be processed for selection of the correct response. Experiments 1A and 2A were designed to enhance the salience of the horizontal dimension by using horizontal effectors, and Experiments 1B and 2B were designed to enhance that of the vertical dimension by using vertical effectors. In contrast, the stimulus display was designed to equate the salience of the horizontal and the vertical dimensions. The S–R mappings paired each effector with two stimulus locations in one dimension (Experiment 1) and in two dimensions (Experiment 2). Experiment 1 showed that the manipulation of response configuration was successful in determining which dimension prevails: Only an HE was obtained in Experiment 1A, whereas in Experiment 1B only a VE was manifested. Experiment 2 showed that when both dimensions have to be processed, HE is obtained irrespective of the effectors used, whereas VE is obtained only when vertical effectors are used. Thus, the right–left prevalence effect was found. This result is problematic for the relative salience account, at least in the version put forward by Vu and Proctor (2001, 2002; Vu et al., 2000). As we mentioned before, Vu and Proctor described salience in terms of environmental features of the S–R sets that enhance a specific dimension. As was shown in Experiment 1, when one spatial dimension is sufficient for selection of the correct response, the salience of the frames of reference used in the present work enhanced the horizontal dimension when horizontal effectors were used and the vertical dimension when vertical effectors were used. One may argue that there was a difference in salience in the two conditions related to the center of the screen. In fact, the response devices were both under the center of the screen, whereas right responses were produced to the right and left responses were produced to the left of the center of the screen. However, when Hommel (1996) had subjects respond with effectors that were above the screen's center (and above eye level too), he did not obtain any differences with respect to when both effectors were under the center of the screen. Thus, when both spatial dimensions are task relevant, an explanation solely in terms of environmental salience does not seem to be exhaustive. We believe that other aspects, which produce a sort of in-

trinsic salience of the horizontal dimension, must be taken into consideration.

An interesting indication in this sense was the longer overall RT in the one-dimensional vertical condition (Experiment 1A) than in the one-dimensional horizontal condition (Experiment 1B). This general slowing for the vertical spatial compatibility task is a rather consistent phenomenon across studies (see Hommel, 1996; Nicoletti & Umiltà, 1984, 1985; Nicoletti et al., 1988; Vu & Proctor, 2001). This is an important issue, because the temporal dynamics of spatial code formation might be one reason that right–left codes affect performance more consistently than top–bottom codes. As Hommel (1996) suggested, if right–left codes are formed earlier than top–bottom codes, it seems reasonable that spatial events are coded primarily on the basis of the horizontal dimension. Here, the bin distributional analysis showed that the HE and VE were of the same magnitude when RTs were short. This finding seems to contradict the idea that horizontal codes are available prior to vertical codes. However, the time course of the HE is rather different from that of the VE. The HE is more or less constant, whereas the VE increases as RTs become longer.

On the whole, when a single code is sufficient for responding, the time course of the HE and that of the VE, together with the overall slowing with vertical effectors, suggests that horizontal spatial codes become available earlier than vertical spatial codes. In contrast, speed of response did not affect the HE and VE in Experiment 2, when both codes were needed for responding. This is reasonable, given that in this case correct response selection must wait for vertical codes because it is based on stimulus codes originating from both dimensions.

Different temporal dynamics occur also in the case of automatic spatial code generation. In a recent study, Proctor, Vu, and Nicoletti (2003) investigated the temporal dynamics of spatial code formation in two-dimensional Simon tasks. The Simon task (Simon & Rudell, 1967; see Hommel & Prinz, 1997, and Lu & Proctor, 1995, for reviews) is very similar to the spatial compatibility task: Subjects respond with right–left effectors to stimuli that appear in right and left locations. However, in the Simon task, subjects are required to select the correct response on the basis of a nonspatial stimulus feature (e.g., color or form). Even if stimulus location is not relevant to the task, on corresponding trials (i.e., those with stimulus and response locations on the same side) response is faster and more accurate than on noncorresponding trials (i.e., those with stimulus and response locations on opposite sides). Thus, the Simon effect is a demonstration that even when they are not relevant to response selection, the spatial attributes of the stimulus are coded automatically and prime the response ipsilateral to stimulus location (see, e.g., De Jong, Liang, & Lauber, 1994, and Kornblum, Hasbroucq, & Osman, 1990, for automatic activation models).

As we found in the present Experiment 1 for spatial compatibility, Proctor et al. (2003) found that the Simon effect for the vertical dimension tends to increase as RT

increases, whereas for the horizontal dimension it does not. Thus, even when stimulus location is irrelevant for the task and spatial coding is automatic, horizontal codes seem to be available earlier than vertical codes.

At this point, one may ask why the horizontal dimension is processed faster. Admittedly, there is no clear answer. It should be noted, however, that in everyday life right-left discriminations are much practiced. As an example, very often we have to choose between the two hands to perform an action, whereas having to choose between a hand and a foot is a much less frequent event. Thus, it is reasonable to assume that the right-left discrimination is overlearned and produces faster processing, which, in turn, enhances the salience of the horizontal dimension (for examples of the effect of learning on S-R mappings, see Tagliabue, Zorzi, Umiltà, & Bassignani, 2000).

Of course, there could be other, non-alternative reasons for which the horizontal dimension is intrinsically more salient than the vertical dimension. In a recent study on two-dimensional Simon effects (Rubichi, Nicoletti, & Umiltà, in press), it has been shown that horizontal coding is based on multiple codes originating from different frames of reference, whereas vertical coding is based on only one frame of reference. Thus, the intrinsic salience of the horizontal dimension may also depend on the number of available frames of reference.

In conclusion, the present study suggests that in two-dimensional spatial compatibility with two relevant dimensions there is right-left prevalence—that is, right-left codes are always formed—whereas top-bottom codes are formed only if vertical effectors are used in responding. To account for the intrinsic salience of the horizontal dimension, the relative salience account should be amended by considering nonenvironmental aspects. Among these aspects, the use of more than one responding hand (Hommel, 1996; Vu & Proctor, 2001), the temporal dynamics in spatial code formation (Hommel, 1996; the present work), and the number of reference frames used for coding (Rubichi et al., in press) seem to play important roles.

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