Directional stimulus-response compatibility: a test of three alternative principles

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Keywords: Compatibility; Reaction time; Psychomotor performance; Direction; Aiming.

Worringham, Charles J. and Beringer, Dennis B. (1998) Directional stimulus-response compatibility: a test of three alternative principles. Ergonomics 41(6):pp. 864-880.

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Abstract

The basis of directional stimulus-response compatibility was studied using a task in which 128 participants moved a cursor into targets with a joystick, resembling the operation of certain industrial and construction equipment. Compatible and incompatible versions of three alternative compatibility principles were compared in all combinations. Visual Field (VF) compatibility was present if cursor and controlling limb movement were in the same direction in the visual field, Control Display (CD) compatibility meant that the control motion was in the same direction as, and parallel to, cursor motion, and Muscle Synergy (MS) compatibility was defined as use of the muscle synergy normally associated with the required direction as seen in the visual field. VF-compatible conditions had significantly shorter reaction, movement and homing times, and fewer reversal errors, for males and females, in two testing sites. These advantages were maintained over practice. VF compatibility was confirmed as a robust spatial compatibility principle that is affected by neither the orientation of the operator's limb or head, nor the muscle synergy used in executing the task. It offers not only more rapid performance, but also a markedly reduced rate of potentially dangerous directional errors. The relationship between this finding and theoretical aspects of stimulus-response compatibility is discussed.

1. Introduction

The inherent tendency to make more rapid and accurate responses given compatible S-R mappings is not only a robust psychological phenomenon whose study has a 40year pedigree (Fitts and Seeger 1953, Fitts and Deininger 1954), but it is also one of considerable practical importance in the design and use of equipment, since many types of machinery yield safe and effective performance only if proper account is taken of compatibility principles. Recent work on stimulus-response compatibility (SRC) has examined the issue from many perspectives (Proctor and Reeve 1990). Amongst these are attempts at general theoretical accounts that cut across a range of tasks, e.g. the 'salient-features coding' model (Weeks and Proctor 1990), and the 'dimensional overlap' model (Kornblum *et al.* 1990). There remains, however, a need to define the rules of compatibility in a lawful and parsimonious way for major classes of tasks. The general theoretical accounts do not, for example, provide much guidance as to which variables are involved in dimensional overlap (Kornblum *et al.* 1990) or how the salient features of stimuli and responses (Weeks and Proctor 1990) may be identified in specific situations.

In this paper the authors focus on the compatibility rules for systems in which a control (e.g. a lever, joystick, or computer pointing device) must be moved to bring about goal-directed motion of a real or virtual object (e.g. a crane-jib, vehicle, or cursor). In such cases, the direction of the control motion must be paired with that of the object motion in some way. What form of directional relationship between the two is compatible? An attempt is made to answer this question by evaluating three possible types of directional compatibility. Before each is presented, it is useful to consider some of the special characteristics of directional SRC that distinguish it from other forms of compatibility.

1.1. *Directional S-R compatibility*

Choosing and executing movements in the correct direction, usually based on visual information, is crucial to most human motor performance. This requires the selective activation of appropriate motorneurones, and thence motor units, and involves a continuous, rather than a discrete mapping between visual direction and motor unit recruitment. A limb can be driven in an infinite number of directions using subtly different patterns of muscle activation. By 'directional compatibility' we mean the degree of congruence between the direction of a control motion (chosen from two or more possibilities) and that of the corresponding system or display motion. Directional compatibility, although of crucial importance in ergonomics, has been given far less (and less theoretically rigorous) attention than have simpler forms of spatial compatibility. In a typical two-choice button-pressing task of the type widely used in SRC research, for example, all that has to be selected is the digit to be used. The movement direction is known in advance, and indeed, is often identical in the available response options.

There is now good evidence from studies of neural function prior to and during goal-directed motion that limb direction is neurally coded in both extrinsic and egocentric coordinates. There are neurones in both motor and parietal cortices that fire preferentially for specific directions of a monkey's aimed arm movement, independent of starting position (Georgopoulos *et al.* 1985, Alexander and Crutcher 1990). In addition, evidence for a coding of the kinematic direction of movement independent of the muscle activation pattern producing it has come from studies of wrist movements in monkeys, in which a particular direction of motion was made either with an assisting or opposing load, or with no load. Many cells in motor but especially parietal cortex were shown to have firing rates well correlated with direction of motion whether this was brought about by (for example) a concentric contraction of wrist flexors or an eccentric contraction of wrist extensors (Kalaska *et al.* 1990). This is direct evidence that a higher level of extrinsic directional coding takes place, distinct from the selective activation of spinal motorneurones, necessarily an intrinsic form of coding. It also suggests the necessity of an intervening transformation, or response selection, process.

Finally, there are some significant practical concerns surrounding the issue of directional compatibility. Many human-machine systems require a control (lever, joystick, rotary knob, etc.) to be moved in a direction corresponding to that of the controlled element or 'display' (which could be a real object, such as a crane jib, or a virtual object such as a cursor on a screen). What defines compatibility in such a case? This is an old problem with no agreed, universally applicable solution, well exemplified by the classic example of three different and potentially conflicting principles for the relationship between direction of knob rotation and direction *of* the indicator in a linear scale-type display—Warrick's principle, the scale-side principle, and the clockwise-for-increase principle (Warrick 1947, Brebner and Sandow 1976, see also Ross *et al.* 1955, and Loveless 1962). More recently, Hoffman (1997) has shown that the applicable principle depends strongly on control and display positions, as well as, to some extent, the population studied. (For example, Warrick's principle, when applicable, was adhered to more strongly by engineering than by psychology students, perhaps because of their knowledge and application of mechanical principles.) In this rather specific case of linear displays and rotary controls, all three principles rest on an identity between the pointer and knob directions, but ambiguity arises because opposite sides of the rotary knob move in opposite directions. For tasks with linear (or near linear) control movements, such ambiguity does not arise. In its place, however, comes the complication of operator orientation. While some devices restrict the operator to a fixed, often seated position, and the controlled object may always be straight ahead, this is often not the case. Many systems force the operator to adopt a variety of orientations to both the control and display. This is frequently true of cranes, hoists, and construction equipment. It would not present any difficulty if the compatibility principle for these movements were extrinsic, because it would be defined fully by the relative directions of the control and the controlled object, without regard to the human operator. As is shown in the following section, however, operator orientation is a critical factor.

1.2. *Possible rules for directional S-R compatibility*

1.2.1. *Control-display compatibility:* Conventional advice from the human factors literature concerning direction is for control-display (CD) compatibility: the simplest interpretation of this is that they should be parallel and in the same direction (using some inertial reference frame). It was shown many years ago, however, that CD compatibility may lead to good performance given one position of the operator relative to control and display but yields very poor performance in another (Humphries 1958, Shephard and Cook 1959), a finding that has been confirmed (Worringham and Beringer 1989). This has led human factors specialists to observe that, for example, 'the direction of movement of a control must be considered in relation to ... the location and orientation of the operator relative to the control, the controlled equipment, and the vehicle' (Chapanis and Kinkade 1972: 355). Unfortunately, the absence of a theoretically based and empirically verified theory of directional compatibility means that practical advice on how to take these factors into account is hard to give.

1.2.2. *Visual-field compatibility:* The authors have proposed that directional compatibility is based on directions defined with respect to the visual field—VF compatibility (Worringham and Beringer 1989). Note the use of the term 'VF' compatibility rather than 'VM' (Visual-Motor) compatibility as in the original report. It more accurately defines the reference frame on which it is based. A VF-compatible situation is one in which the motion of the relevant limb segment is in the same direction as that of the 'controlled element', or 'display', as seen in the visual field. Usually, the limb holding the control is aligned, at least approximately, with the display, as in a normal seated position with arm and hand held in front of the body. In this position, several distinct forms of compatibility are simultaneously present. No distinction between them is therefore possible. In addition to VF compatibility, the control and display motions are parallel to one another and in the same direction, and thus this situation also embodies CD compatibility Consider a case, though, in which the individual looks over the left shoulder to view a display with the right arm outstretched to the right holding a control. CD and VF compatibility now become mutually exclusive. If the appropriate control motion is in the same direction as, and parallel to, the display motion, then it is CD- but not VF-compatible. Conversely, if the opposite motion is required, VF compatibility exists but CD compatibility does not.

In a target acquisition task using eleven combinations of arm and body positions and control-display relationship, it was shown that movements were initiated and executed up to eight times faster in VF-compatible conditions. Thus, even when the participant looks in the opposite direction from the controlling limb, a rightward movement of the cursor (rightward in the visual field) was best achieved with a rightward movement of the limb as seen in the 'virtual' visual field (the visual field that would be present were the participant looking at the limb and not the display) Note that the directions of display and control motions, with reference to their absolute spatial directions, are now opposite, showing that simple correspondence between the two, CD compatibility, is not generally valid. The authors therefore proposed that VF compatibility was a universal principle of directional compatibility that was independent of viewing and limb positions (Worringham and Beringer 1989).

1.2.3. Muscle synergy compatibility: There is, however, an alternative interpretation of these results. Rather than compatibility stemming from visual field directional correspondence, an individual may simple employ the muscle synergy (muscle activation pattern, e.g. flexion or extension, abduction or adduction, pronation or supination of a given joint) normally associated with a visually specified direction A rationale for this as a plausible coordinate scheme can be offered readily Imagine a control motion involving extension or flexion of the right wrist. In everyday movements, such as the moving or manipulation of objects, right wrist extension would be associated with a movement in the visual field either to the right or with a strong rightward (and often an upward) component. The reverse (leftward) would be true in general, for flexion. These relations hold because most actions take place with the limb in view, the forearm about midway between full pronation and full supination, and the forearm either parallel to the midline or within a few tens of degrees of this plane. Admittedly, natural motions typically also involve other joints, but this does not invalidate the analysis. Only in certain extreme positions is this relationship between muscle synergy and visually-defined direction completely disrupted. One occurs with the elbow extended and forearm fully pronated (sometimes combined with internal rotation of the humerus) to point the thumb downwards. Now a right wrist extension appears as a leftward movement in the visual field. A second case requires the right upper arm to be horizontal and parallel to the midline, the elbow and wrist to be mostly flexed, and the forearm supinated (thumb up). In this position the fingers and thumb point toward the chest, and wrist extension is also viewed as leftward. These extreme postures may be uncomfortable, however, and are avoided when possible (for example, see Rosenbaum's examination of spontaneous grasp orientations, Rosenbaum *et al.* 1990, Rosenbaum 1991).

It is reasonable to suppose that a fairly direct association between normal visually defined direction and muscle synergy is either inherently present or comes to be formed as a consequence of the innumerable visually directed manipulations performed each day. If so, and if the same muscle synergy is still used when its direction is incompatible in visual field terms, then directional compatibility could be explained as 'muscle synergy' (MS) compatibility.

Such a possibility is reminiscent of the type of 'spatial-anatomical' mapping that has previously been compared to 'spatial' mapping in button-pressing choice reaction time (RT) tasks. A notable and reproducible observation is that relative spatial position rather than anatomically defined side (i.e. hand or arm) accounts for performance. For example, Wallace (1971) showed that responses were faster for the hand nearer the stimulus light even when the hands are crossed so as to put the left arm closer to the right stimulus (and vice versa). This suggests that a spatial-anatomical mapping is not normally used. Others have provided confirmation for the primacy of relative spatial position (Brebner *et al.* 1972, Anzola *et al.* 1977, Nicoletti *et al.* 1984). The notion of a hierarchical system of compatibility has also been advanced, in which spatial (relative position) mapping predominates over spatial-anatomical mapping except when the former is ambiguous (Heister *et al.* 1986, 1990). There is consensus that spatial-anatomical mapping is at least subordinate to spatial mapping. However, these studies, which involve the choice of responding with one anatomical unit rather than another (e.g. left or right index finger), do not preclude the existence of a form of spatial-anatomical mapping in which particular muscle groups of a single segment tend to be activated for a particular direction of motion.

1.3. *Comparison between CD, VF and MS compatibility types*

The experiment described below was designed to distinguish between these three explanations (VF, MS and CD compatibility). It required that compatible and incompatible versions of each be presented in all possible combinations, so that the effects of each (and possible interactions) could be properly evaluated. The experiment was fully replicated in our laboratories in Ann Arbor and Las Cruces.

2. Methods

2.1. *Tasks*

Subjects used a joystick arranged to record wrist flexion or extension and drive a cross-shaped cursor into a red elliptical target, I cm wide, 1.2 cm high, shown on a computer screen (black background) in the shortest possible time following the simultaneous presentation of cursor and target. The cursor had to be held on target for a 300 ms criterion period for a trial to be concluded successfully: this was indicated by the target turning from red to blue. For each block, targets were randomly sampled without replacement from eight possible locations, four to the left and four to the right of centre, at distances 1.75, 3, 4.5 and 6 cm.

An additional task, pursuit tracking for 30 s, was administered at the beginning of each session. Its purpose was to provide an independent estimate of ability on a related perceptual-motor task, so that the equivalence of groups could be verified. A target, moving up and down the centre of the computer screen and generated by summed sinusoids, had to be tracked with a cursor controlled by a rotary knob held in the fingers and thumb of the right hand. The control knob's axis of rotation was along the transverse (medial-lateral) axis, and target and cursor motion were vertical, to ensure that this task had no directional component in common with the main task. Root mean square (RMS) error was the dependent variable.

2.2. *Apparatus*

A specially designed joystick attached to the end of an arm-rest was mounted on a chair (Las Cruces) or a tripod (Ann Arbor) adjacent to the chair, so that its position could be readily adjusted (in front or behind the participant, and at a comfortable height). The joystick moved radially about a vertical axis co-linear with the wrist and used zero-order (position) control. This physical design was used to restrict the muscle groups used, as much as possible, to wrist flexors or extensors, and reduce biomechanical coupling effects. A microcomputer and 14-in flat-tension mask colour monitor were used at each site to read joystick position, present the target and cursor, and collect data. Viewing distance was approximately 1.5 m at eye level. Control software allowed the direction of joystick motion to correspond to leftward or rightward cursor motion on the screen as needed for each condition.

The same computer and monitor used in this task was also used to control the screening task (pursuit tracking).

2.3. *Participants*

A total of 128 right-handed young adults (64 men, 64 women) participated, in exchange for course credit. Half of the participants, 32 men and 32 women, were tested at each site, and all provided informed consent.

2.4. *Design*

A mixed-model factorial design was used, involving five factors with two levels and one factor with seven levels. Two-level factors were VF compatibility, MS compatibility and CD compatibility (compatible or incompatible in each ease); Location (the experiment was fully replicated in Ann Arbor and Las Cruces), and Gender (an equal number of males and females were used in each condition). The latter two were not of primary experimental interest but provided for replication and generality. Block was a seven-level repeated measures factor, and consisted of consecutive groups of eight trials.

Figure 1 shows the set-up for each of the eight combinations of the three compatibility types. These were achieved by combining different types of CD compatibility (normal or reversed) with two different body and wrist positions. Subjects either sat facing the screen or sat sideways with gaze and right arm in opposite directions, and they had the forearm either supinated (thumb up) or pronated (thumb down). Each participant was assigned to a single combination of the three compatibility types. Thus VF, CD, MS, Gender and Location were between-subject factors, and Block was a repeated measures factor.

2.5. *Procedure*

After giving informed consent and receiving initial instructions, each participant was seated at the apparatus for the compatibility task, and adjustments to chair and armrest position were made to provide a comfortable position for testing. The pursuit tracking task was administered first, after which the participant was seated in the position appropriate for the particular condition to which he or she had been allocated. Instructions were then read aloud by the experimenter. Each trial was to be completed in the shortest possible time, but no information was given as to how the control direction corresponded to the cursor direction. There was a rest break of a few minutes between blocks 4 and 5, during which the participant was allowed to change position and stretch if desired. Following completion of testing, participants completed a short questionnaire concerning discomfort and fatigue, as well as previous experience in different types of perceptual-motor task. These results are not reported here as they showed no relationship to the compatibility factors under study.

3. Results

3.1. Pursuit tracking task

There was no difference between the RMS error on the pursuit tracking task between the groups designated as compatible or incompatible, whether this was defined by VF, CD or MS compatibility ($p > 0.4$ in all cases). Thus the remaining results for the main task are not the result of inadvertent allocation of individuals with superior perceptual-motor ability to the different compatibility conditions.

3.2. *Aiming task*

The requirements of the task were to acquire the target as rapidly as possible. The three temporal measures are therefore presented first, followed by error frequency data.

3.2.1. *Reaction time:* This measure was the interval between target presentation and the initiation of joystick movement, and can be thought of as an index of preparatory or planning processes. Means for the eight combinations of compatibility type are shown in figure 2a. VF-compatible conditions had significantly shorter RTs than did VF-incompatible conditions, $F(1,96) = 20.51$, $p < 0.0001$). The advantage was approximately 100 ms on average (531 versus 627 ms). While both these times are longer than those typically encountered in 2-choice RT tasks, it must be remembered that participants had to minimize total response times, not RTs, and received no instructions or feedback about the latter.

There was no significant main effect for either of the other compatibility types (CD compatibility: $F(1,96) = 1.36$, $p>0.2$; MS compatibility: $F(196)< 1$, $p>0.6$). In both cases, the nominally compatible version of the task was initiated slightly more slowly, on average. There were no interactions between compatibility types ($p>0.1$ in all three 2-way interactions and the 3-way interaction).

Subjects in all conditions benefited from their practice of the acquisition task, yielding a significant Block effect, $F(6,576) = 40.44$, $p<0.0001$. Block showed no interaction with any compatibility condition, however. An example of this is seen in figure 3a, for VF-compatible and VF-incompatible RTs. The advantage for the former is preserved across the seven blocks.

There were additional minor effects not directly related to the issue of compatibility. Subjects tested in Ann Arbor had faster RTs than those in Las Cruces (544 versus 614ms), $F(1,96)= 10.70$, $p<O.005$; but improved less over blocks, $F(6,576) = 2.52$, $p < 0.05$, and, regardless of site, men responded some 90 ms faster than women, $F(1,96) = 17.83$, $p<0.0005$.

3.2.2. *Movement time:* This measure—the interval between movement initiation and the first entry into the target—formed the largest component of the overall response duration, and also showed a significant 74 ms advantage for the VF-compatible over the VF-incompatible conditions, 692 versus 766 ms, $F(1,96) = 13.31$, $p<0.0005$. This advantage was seen at all combinations of the other compatibility factors (figure 2b). CD and MS compatibility showed no significant main effects ($F< 1$ in both instances), nor did the three compatibility factors interact. Block had, again, a significant effect, F(6,576) = 51.08, $p<0.0001$, such that all groups became substantially more rapid as blocks of trials proceeded (figure 3b). The only significant effect other than one uninterpretable 4-way interaction was that the Las Cruces group had movement times (MTs) that were an average of 99 ms faster than Ann Arbor participants, F(1,96) = 24.31, $p<0.0001$.

3.2.3. *Homing time:* This measure assessed the performance in the terminal phase of the movement, being the interval between first entering the target and finally entering it. It would have a zero value if the cursor is kept within the target, otherwise it reflects the time taken to re-enter the target and stay in it for the criterion period. On average, homing time (HT) was just over half the magnitude of MT. Figure 2c shows that there was, once again, more rapid performance for those in VF-compatible than VF-incompatible conditions: 338 versus 445 ms. This 107 ms advantage was statistically significant, F(1,96) = 44.97, $p<0.0001$. As before, neither CD nor MS compatibility showed main effects. The CD factor approached significance, F(1,96) = 2.97, $p<0.09$, but the CD-incompatible times were shorter than the CD-compatible values.

The MS factor did not approach statistical significance ($F< 1$). The HT values fell significantly over the course of practice, as shown in figure 3c and by the main effect of block, F(6,576) = 54.83, $p < 0.0001$. This improvement did interact with the VF compatibility factor, F(6,576)= 15.43, $p<0.0001$, an effect also depicted in figure 3c. Here it can be seen that most of the improvement occurred in the VF-incompatible conditions, with VF-compatible times being almost unchanged following the initial drop from block 1 to block 2. The gap between the conditions fell from 214 to 40 ms with practice. The VF-compatible versions were significantly shorter in all but the final block ($p<0.05$, Tukey's pairwise comparisons). Of the secondary factors, there were three significant effects (excluding one 3-way and one 4-way interaction, each of which lack a clear interpretation). First, the Las Cruces group was slower overall, F(1,96) = 20.88, $p<0.0001$, but, second, they showed more improvement over blocks than those tested in Ann Arbor, reducing their 127 ms disadvantage to one of 54 ms between blocks 1 and 7, F(6,576) = 3.96, $p < 0.001$, for the Location x Block interaction. Third, the mean HTs of women were 67 ms longer than those of men, F(1,96) = 18.05, $p<0.0001$).

3.2.4. *Movement direction errors:* In addition to the preceding temporal measures, the occurrence of direction, or reversal errors, served as a measure of performance, even though it was not explicitly penalized. Initiating movement in the wrong direction would be disadvantageous, however, as the ensuing correction would cost significant time. Such errors were not especially frequent, occurring on just 10% of all trials. As figure 2d shows, however, their distribution was far from even, being more than one order of magnitude more frequent in the VF-incompatible than the VF-compatible conditions. Neither MS nor CD compatibility factors showed main effects ($p>0.05$). The only other significant effects involved change with practice. First was an overall effect of block, $F(6,576) = 41.78$, $p<0.001$, together with an interaction between block and VF compatibility, $F(6,576) = 16.85$, $p<0.001$. As was the case for homing time, the bulk of the improvement occurred in the VF-incompatible group. Both these effects are shown in figure 3d. Despite the convergence of the VF-compatible and VF-incompatible groups, the advantage for the former was significant for all seven blocks ($p < 0.05$, Tukey's pairwise comparisons). By the seventh block it manifested an absolute floor effect, since none of the 512 combined trials made by those in VF-compatible conditions included any reversal errors. A total of 60 such errors were made, in total, by the VF-incompatible group in this block, however.

When movement errors were made, they tended to be larger (i.e. the initial incorrect movement covered a greater distance before being reversed) in VF-incompatible than in VF-compatible conditions (by 44% on average). This could not be tested statistically, because the number of errors in VF-compatible conditions was extremely small. CD-compatible errors were 20.1% shorter than CD-incompatible errors, and MS-compatible errors were 10.4% longer than errors in MS-incompatible trials. As there were relatively few errors and many missing cells, statistical analysis of these differences was also precluded.

4. Discussion

The experiment provided clear evidence that VF compatibility governs performance in this type of discrete aiming task. The validity of CD compatibility was not supported. Further, one can reject the possibility that participants tended to make responses on the basis of muscle activation patterns associated with visually-defined directions (MS compatibility). In this discussion the authors first consider possible alternative explanations, then discuss some of the implications of these findings for the theoretical basis of SRC, as well as some specific characteristics of this experiment, the task, and the effects of practice. Finally, the practical applications of these results are considered.

4.1. *Subject selection, fatigue and position effects*

It is necessary first to rule out aspects of the experimental conditions that could have inadvertently influenced the results. First, none of the groups differed in the performance of a common, pursuit-tracking task, so it is highly improbable that participants in the experimental groups were not comparable with respect to general perceptual-motor proficiency. Second, in half of the conditions used in the present study, the physical positions maintained by the participants (head and arm positions) were unusual, and therefore potentially fatiguing or uncomfortable. This is especially the case when the head is rotated to the left and the arm to the right in a pronated position. Any such effects cannot explain the compatibility results, however, since compatible and incompatible versions of each of the three forms of compatibility tested here included an equal number of forward-facing and side-facing postures, and an equal number of pronated and supinated forearm positions. In fact, when the pronation/supination and forward/sideways facing factors were tested independently with ANOVA, neither was significant for any of the three time measures or for the error frequency data ($p>0.5$ for seven of the eight comparisons; $p>0.1$ for the pronation/supination factor: MT variable; df = 1,112 in all cases). Moreover, serial order effects and interactions between conditions were not present because a between-subjects design was used. Thus the results may be attributed to the compatibility conditions *per se.*

4.2. *Theoretical implications*

This experiment confirms the general primacy of spatial over spatial-anatomical mapping for SRC phenomena (Wallace 1971, Brebner *et al.* 1972, Anzola *et al.* 1977, Heister *et al.* 1990), but in a different form. Previous reports have supported a spatial mapping by showing that compatible responses do not involve a fixed linkage between the location of the stimulus and the use of a particular anatomical segment (e.g. finger or hand). The current experiment, however, shows that muscle groups with opposing functions around a given joint can be equally compatible, depending on their direction in the actual, or virtual, visual field. Although only a subset of possible head and limb orientations were used in the current study, it confirmed the results found for VF compatibility in a previous report (Worringham and Beringer 1989). Since the earlier experiment used at least two different physical orientations for each form of compatibility, one would expect the current results to generalize fully to positions that were not tested, provided they are valid instantiations of the VF compatibility principle.

The current study is relatively neutral with respect to certain general theories of SRC. In the terms of Kornblum *et al.* (1990), it could be taken to demonstrate which stimulus and response dimensions overlap, and how. Similarly, it could be thought of as showing which features of the task are 'salient' (Weeks and Proctor 1990). On the other hand, these results do lend weight to the notion of an egocentric reference frame for stimulus identification, that may then be mapped on to the appropriate motor output, as suggested by Ladavas and Moscovitch (1984) (see also Umilta and Liotti 1987). In their study, participants had to press one of two buttons, which were arranged orthogonally to the stimuli (stimuli top or bottom: vertical; buttons left and right: horizontal, or vice versa. For example, with the head tilted 90° to the left, a pair of vertically arranged stimuli could be seen (egocentrically) as left or right, and the appropriate limb then used for the response. In a variation of this task, Schroeder-Heister *et al.* (1988) included a crossed-hands condition. With head tilted and hands crossed, spatial compatibility effects were decreased and there was a tendency to respond with the hand that is (anatomically) on the same side as the stimulus is perceived to be on. The present study uses head rotation around a vertical axis rather than head tilt, but is similar in that the stimulus coding (in this case the direction of a target relative to a starting position), can be thought of as visual-field (i.e. head) centred.

4.3. Processing stages and proprioception

The advantage shown by VF-compatible conditions was not restricted to one phase of the response. There was no requirement to minimize any particular component of the overall duration; rather, the whole response had to be made as quickly as possible. Significant benefits were found for reaction time, movement time, and homing time, however. Thus it may be assumed that VF compatibility exerts its effects during both movement planning and all phases of execution. Additional evidence for an effect in movement planning is the large disparity in movement direction errors. It seems reasonable to suppose that in VF-incompatible conditions, a VF-compatible response is planned by default. This has to be checked before initiation, and changed if necessary, a step that is not always successful and requires some 100 ms of additional processing. This checking process is similar to that envisaged by Kornblum for incompatible versions of a variety of tasks (Kornblum *et al.* 1990).

It is apparent that participants selected either an extension or a flexion as the appropriate motion quite readily, depending on limb position. The authors speculate that there is a common neural mechanism for this 'switching' and for the crossed-hands effect reported by Wallace (1971), Brebner *et al.* (1972), and Anzola *et al.* (1977). In the latter, the hand on the same side as the stimulus is spontaneously chosen, e.g. left hand for left stimulus if the hands are uncrossed; right hand for left stimulus if the hands are crossed. It seems likely that proprioceptive information about limb position, which is available before the stimulus appears, is used in the process of selecting the appropriate response. How the proprioceptive signal is incorporated into response planning remains unclear, but one possibility can be excluded. It seems unlikely that participants selected the appropriate VF-compatible movement for a normal, supinated (thumb-up) position and then reversed the selected movement if the forearm was pronated, as this could be expected to add a constant to the reaction time. Responses made in the unusual pronated (thumb-down) position were not significantly different from those in the supinated position trials, however, being 578 and 580 ms, respectively ($F(1,112) = 0.01$, $p>0.9$).

4.4. *Gender and experimental location effects*

The lack of an interaction between either location or gender with the compatibility factors demonstrates that men and women are both governed by the VF compatibility principle, and that the latter is robust enough to yield the same outcome in different laboratories. There were some main effects of gender and location, however. Women tended to have longer RTs and HTs. This was tentatively attributed to the ability of men to generate slightly higher joint torques, making it easier to overcome the opposition of movement by the joystick centring springs. This would have its effect primarily when accelerating the control, as occurs at both movement initiation and in issuing final corrections at the end of a movement. The somewhat longer RTs and HTs (but shorter MTs) for the Las Cruces group may have stemmed from slightly different physical characteristics of the controls, possibly the spring stiffnesses. In any event, these minor results have no bearing on the question of directional compatibility.

4.5. *Practice effects*

The number of trials, 56, was quite small and certainly would not represent the amount of practice that operators tend to have with real systems. The analysis of block effects, nevertheless, showed that the VF compatibility advantage was retained over blocks for RT and MT, which, together, comprised 77% of the overall response duration. The corresponding advantage in HT was initially substantial but decreased with practice, and was not statistically significant by block 7. Why was there no compatibility effect for this measure by this stage? Subjects may have become more adept at using errors early in the execution of each trial to determine the compatibility rule, and put it into effect towards the end of a trial. Alternatively, they may simply have learned the system gain (amplitude scaling) irrespective of compatibility, and been generally better at not passing through the target. The conditions would converge as a floor effect is reached. Movement reversal errors were substantially less frequent in VF-compatible conditions, but also fell more with practice in VF-incompatible conditions. A floor effect is clearly manifest here, however, since VF-incompatible movement reversals became practically nonexistent. Note also that the convergence was insufficient to prevent error rates being significantly higher in VF-incompatible conditions even in the later blocks.

Overall these block effects suggest that practice decreases but does not eliminate the advantage of compatibility. This finding is in agreement with Dutta and Proctor (1992) whose SRC study, although using a different task involved a much larger amount of practice (2,400 trials). The exception was for HT. although this component accounted for under one-quarter of the response duration and may have explanations unrelated to compatibility. It would be of considerable interest to study the influence of extended practice on VF-compatible und VF-incompatible performance in a single group of participants. In both the present study and that of Dutta and Proctor (1992), each participant only practiced a compatible or an incompatible version of the same task. Real systems may require a single operator to cope with both versions. Recently, evidence has been presented that more than a 3; single visual-motor mapping can be simultaneously represented in the nervous system (Cunningham and Welch 1994). In their study, interference still occurred when switching between mappings, however, but was confined to the initial 10 s of the 33 s pursuit tracking trials. In discrete tasks, such as that used here, such slow adaptation would be of little or no benefit.

4.6. *Practical implications*

It was found that participants did not base their responses on the muscle synergy principle. The facility shown in using either of two opposing muscular and kinematic actions, as appropriate for the pronated or supinated arm positions, clearly shows that for this task, performance was equally proficient however the handle was grasped (manifest in the lack of any MS main effect). Caution must be exercised in its application here, however, unless a particular configuration is carefully tested. First, participants in the current study performed blocks of trials with the limb in the same position (pronated or supinated). If a control is grasped so as to require a different activation pattern infrequently, one cannot rule out the possibility that there is some effect of the type of grip. Second, there are many types of control and for some, the performance level may be highly dependent on the manner in which it is held, for reasons that may have nothing to do with issues of compatibility. The safest rule is probably to design controls so as to discourage unusual grips, a criterion that would in any event accord with spontaneous grip preference (Rosenbaum *et al.* 1990, Rosenbaum 1991).

Many systems do not require the operator to view the controlled object in a direction that is different from that of the control. This occurs, for example, in equipment with fixed seats mounted in cabs that swivel with the controlled device. In these cases, CD and VF compatibility are indistinguishable, and it is of theoretical rather than practical significance that the latter appears to be the principle on which performance is based. Other systems, however, permit or even *require* a great range of viewing and control orientations, and it is in these cases where the discrepancy between the two becomes important. Truck-mounted cranes, overhead hoists, and systems with fixed controls around which the operator may take up different positions, are examples.

This study confirms the viability of VF compatibility as a principle that may be applied to the design of such human-machine systems, and as one that is independent of the physical orientation of the human operator with respect to control and display (Worringham and Beringer 1989). Possible exceptions and situations that complicate the application of this rule are discussed below. Nevertheless, in many settings the operation of VF-compatible systems should not simply be more rapid, but safer. Consider, for example, the implication of the reversal error data for a system in which the wrong direction of motion could lead to injury or damage (such as a load suspended from a crane being directed away from rather than towards its destination). Such errors need not be frequent to be serious, but they occurred in nearly 20% of trials in VF-incompatible conditions, as opposed to just over 1% of VF-compatible trials, overall. Furthermore, when they did occur, the cursor displacement tended to be larger. A plausible explanation for this is that the very infrequent errors made under VF compatibility could be *corrected* rapidly because they are *detected* rapidly. Detection may precede movement-related sensory feedback if the individual selects the 'wrong' movement according to the VF rule. In VF-incompatible conditions, however, movements that turn out to be in the wrong direction occur when they are planned correctly according to the VF rule, and such errors may only be detected once they become apparent through visual or other sensory inputs (Higgins and Angel 1970, Megaw 1972). Given that VF-incompatible direction errors are much more frequent and that these movements tend to travel further in the wrong direction before being corrected, it can reasonably be expected that systems that obey the VF compatibility principle, compared to equivalent systems that do not, will enjoy an overwhelming advantage in terms of minimizing errors, incidents and accidents.

The apparent validity of this directional compatibility principle cannot, however, absolve the designer of responsibility for investigating carefully whether some *non-directional* compatibility principle may be salient for a particular system. In keeping with the concept of dimensional overlap introduced by Kornblum *et al.* (1990), it must be accepted that many other types of mapping may exist between stimuli and responses (e.g. colour coding). Fortunately, there is much evidence that spatial coding influences performance strongly even where the spatial characteristics of the mapping are not the rules that the operator is supposed to use (i.e. the Simon effect; Simon *et al.* 1970). Nevertheless, it is prudent to apply this rule only after ascertaining that directional mapping is clearly predominant, and that other mappings do not play a major role.

A second note of caution should be sounded with respect to complexities that may arise in systems that do not follow a simple—or a single—directional mapping. For example, two parts of the device may respond to a single control motion, and in different directions. Control motions may be limited to one or two degrees of freedom when the controlled device has three degrees of freedom. Conversely, two separate control motions may summate to produce a single device motion (e.g. simultaneous luffing and slewing in a crane resulting in a diagonal motion of the load). Some of these more complex situations do not invalidate the VF rule. For example, it applies to zero-, first- and second-order control systems despite the reversals needed in the second two for a unidirectional output motion (Worringham *et al.* 1997). Other complexities have not been adequately studied and deserve more consideration on both theoretical and practical grounds, however.

Acknowledgements

The authors are grateful to Kathleen Hinderer (Ann Arbor) and the late G. Larry Short (Las Cruces) for their assistance with data collection. Some of these results have been published previously in abstract form.

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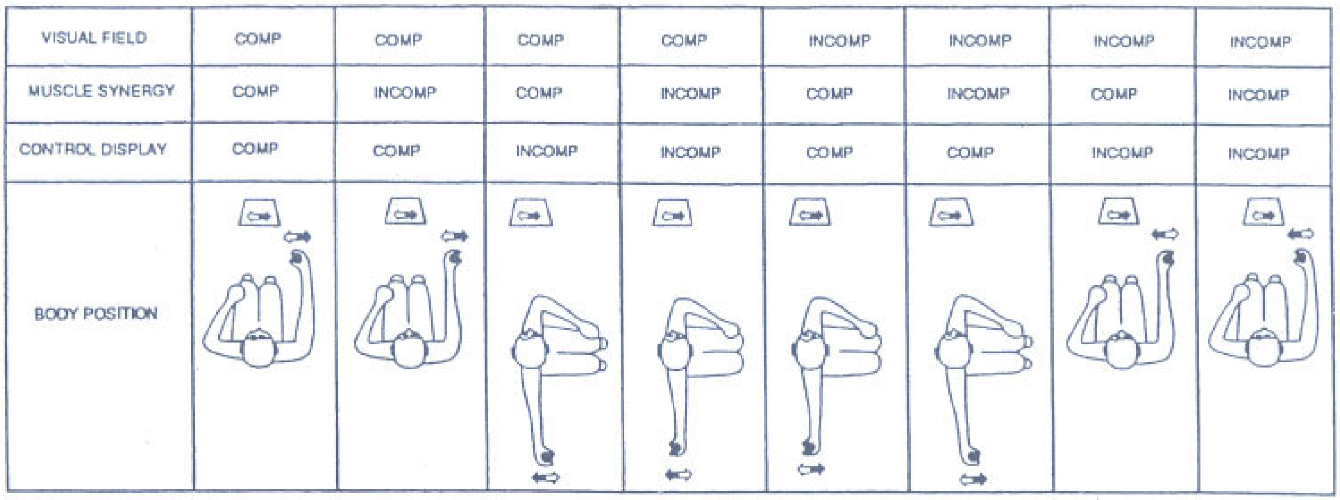

VISUAL FIELD	COMP	COMP	COMP	COMP	INCOMP	INCOMP	INCOMP	INCOMP
MUSCLE SYNERGY	COMP	INCOMP	COMP	INCOMP	COMP	INCOMP	COMP	INCOMP
CONTROL DISPLAY	COMP	COMP	INCOMP	INCOMP	COMP	COMP	INCOMP	INCOMP
BODY POSITION								

Figure 1. Plan view of head, trunk and limb orientation for each condition. The filled (or unfilled) end of the arrow adjacent to the hand shows the joystick direction required to move the cursor in the direction shown by the filled (or unfilled) end of the arrow in the representation of the screen at the top of each panel. The first two panels show, respectively, examples of supinated and pronated forearm positions.

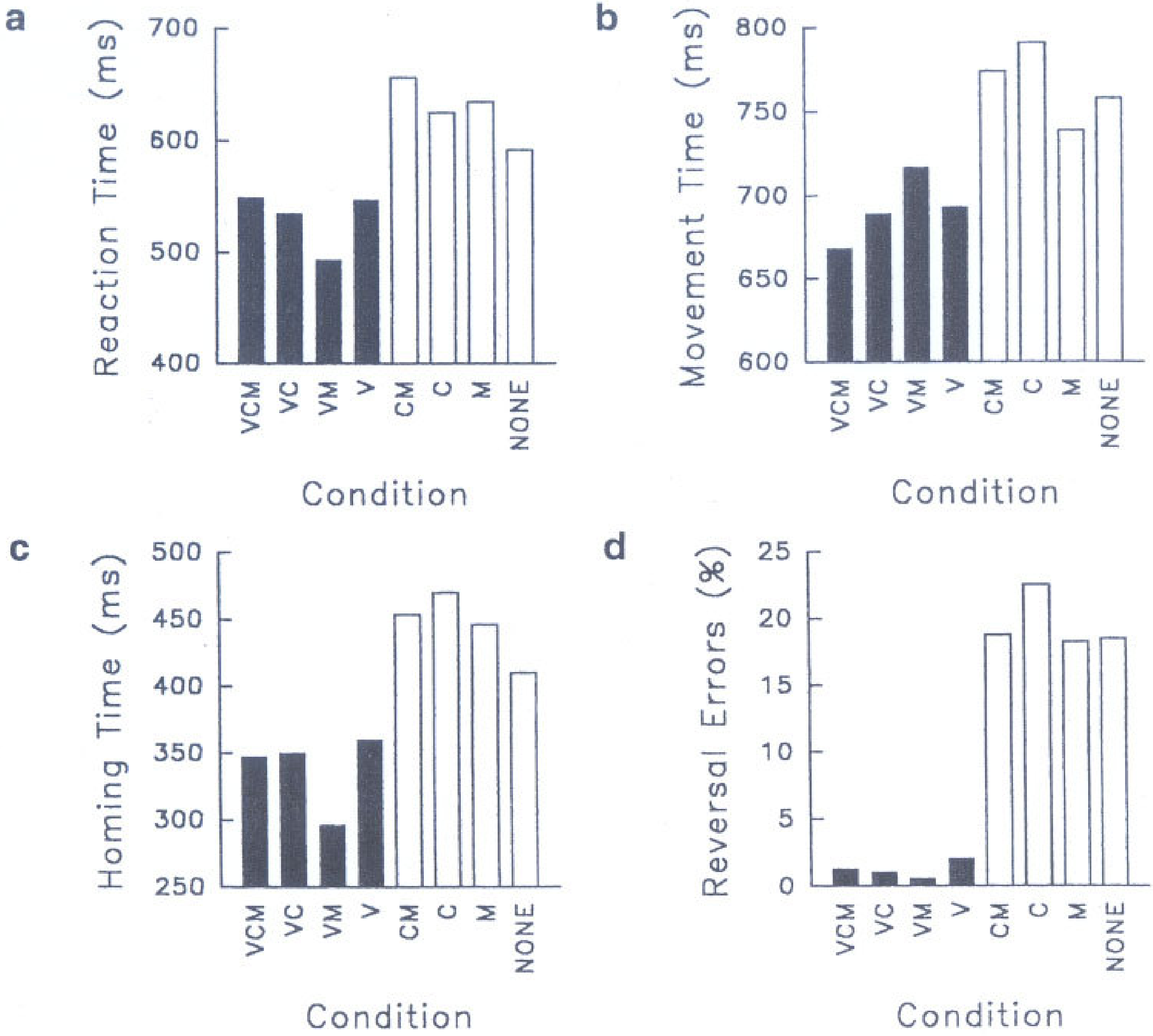

Figure 2. (a) Reaction time, (b) movement time, (c) homing time, and (d) reversal error rates. V, C and M denote, respectively, that conditions were compatible according to visual field, control-display, and muscle synergy compatibility types. '0' denotes the condition that was incompatible according to all of these compatibility types. VF-compatible conditions are shown with filled bars.

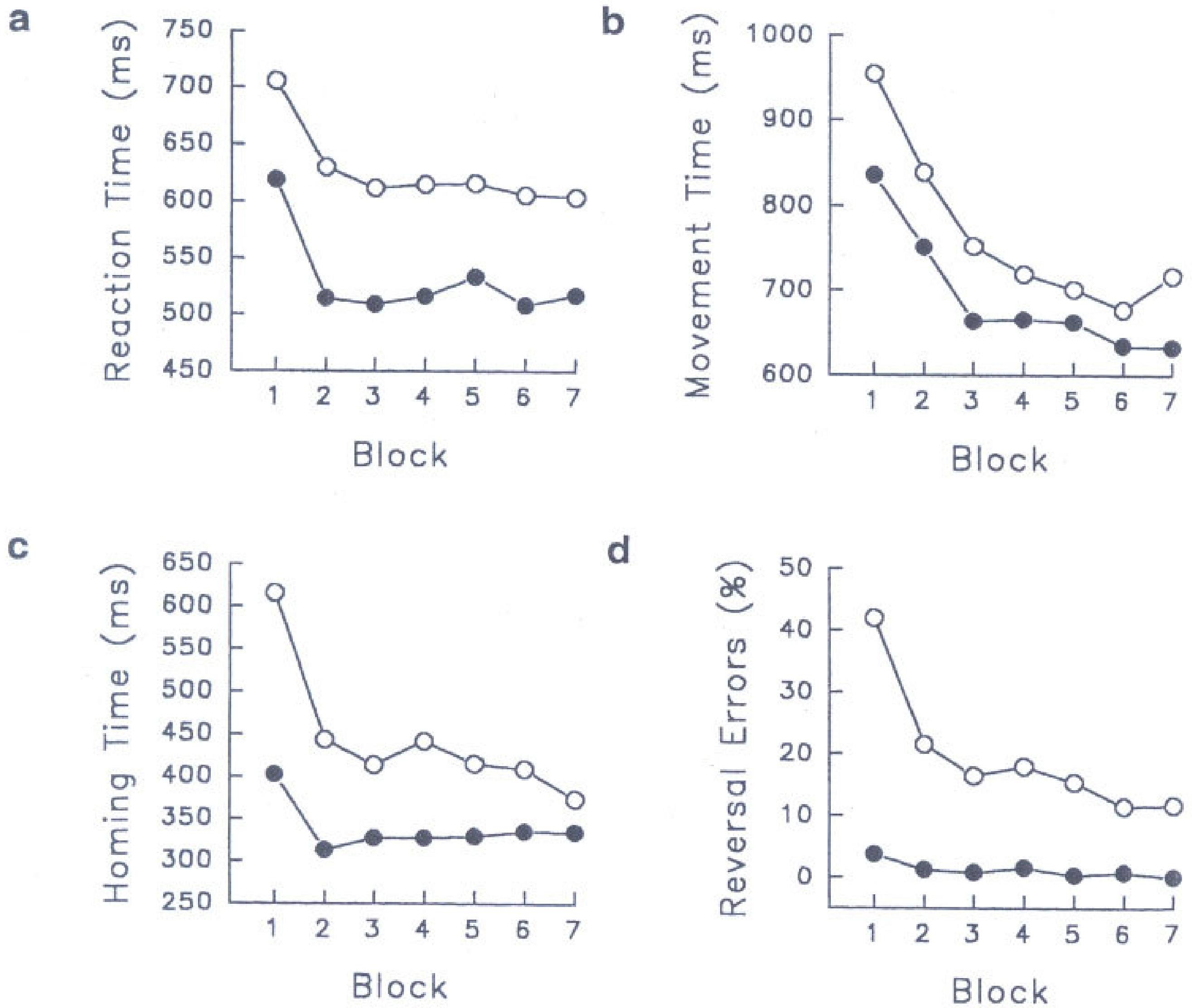

Figure 3. (a) Reaction time, (b) movement time, (c) homing time, and (d) reversal error rates for VF-compatible (filled circles) and VF-incompatible conditions (unfilled circles) for the seven blocks of trials.