

On the Relations Between Seen Objects and Components of Potential Actions

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Accounts of visually directed actions usually assume that their planning begins with an intention to act. This article describes three experiments that challenged this view through the use of a stimulus–response compatibility paradigm with photographs of common graspable objects as stimuli. Participants had to decide as fast as possible whether each object was upright or inverted. Experiments 1 and 2 examined the effect of the irrelevant dimension of left–right object orientation on bimanual and unimanual keypress responses. Experiment 3 examined wrist rotation responses to objects requiring either clockwise or anticlockwise wrist rotations when grasped. The results (a) are consistent with the view that seen objects automatically potentiate components of the actions they afford, (b) show that compatibility effects of an irrelevant stimulus dimension can be obtained across a wide variety of naturally occurring stimuli, and (c) support the view that intentions to act operate on already existing motor representations of the possible actions in a visual scene.

The use of vision to control actions has typically been framed as a problem that begins with the intention to act. How we use visual information depends, after all, on the goal of the action. Grasping a ball and kicking it require both representing different visual information and transforming that information into very different muscle commands. In this article we explore the possibility that visual objects potentiate actions even in the absence of explicit intentions to act.

There are many reasons for supposing that a representation of the visual world includes information about possible actions. Perception and action are intimately linked. Our decisions to act are not made in a vacuum but are informed by the possibilities inherent in any visual scene. In this sense, vision is important for providing information about what actions are possible, as well as for the on-line control of their execution. Furthermore, knowledge of the possibilities for action depends critically on the relation between the visual world and the physical apparatus of the perceiver—a point long emphasized in the ecological approach to perception and action. How might such action possibilities be represented? A plausible proposal is that the perception of an object (or scene) results in the potentiation of the actions that

can be made toward it (or within it) and that this potentiation involves the actual activation of motor representations of those acts. Obviously there are effectively an infinite number of possible actions that can be made toward even a single object, and one must presume that those most highly associated with the object are also those most highly activated. Not all the actions that can be made toward an object can be made toward it given a particular state of the perceiver. One of the actions that can be made toward a saucepan, for example, is a reach-and-grasp movement, but this cannot be made if the saucepan is beyond the reaching space. Thus the position of the object with respect to the observer will also affect the actions most highly activated. We do, after all, possess strong associations between objects and the actions commonly carried out with them (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), which reflects the fact that an object's function is intimately bound with the actions we direct to it. This association is not restricted to high-level actions such as writing with a pen but is also apparent at the microscopic level such as in the hand shape required to grasp it (e.g., Klatzky, Pelligrino, McCloskey, & Doherty, 1989; Klatzky, Pelligrino, McCloskey, & Lederman, 1993).

In the following, we first outline some of the neurophysiological data that make the proposal plausible and then describe a behavioral paradigm (stimulus–response compatibility) that is well suited for studying the automatic activation of motor responses. Finally, we describe three experiments that provide some preliminary evidence in support of this view.

Neurophysiology of Vision and Action

The visual system is highly integrated with the motor system to the extent that no clear divide exists between what one could call purely visual processing and purely motor processing. The transition from one type of representation to the other does not occur in discrete serial steps correspond-

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ing to individual cortical areas. The major pathway involved is the projection from the primary visual cortex to the posterior parietal cortex, known as the dorsal pathway, and from there to the premotor and motor areas. The dorsal pathway was originally thought to be primarily involved in spatial processing—the “where system” in contrast to the “what system” of the ventral pathway, responsible for object recognition and pattern discrimination (Ungerleider & Mishkin, 1982). More recent neuropsychological evidence, however, has implicated the dorsal pathway in all aspects of visuomotor activity (Goodale, 1993; Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1993). This evidence has shown that damage to the ventral system can result in a condition known as visual form agnosia, in which the recognition of simple object properties such as size and orientation, as well as location, is impaired, whilst the ability to use that information to make accurate reaching and grasping movements is preserved. In contrast, optic ataxia, resulting from lesions to the parietal lobe (in the dorsal system), is characterized not only by object mislocalization but also by deficits in the preshaping of the hand (Jakobson, Archibald, Carey, & Goodale, 1991; Perenin & Vighetto, 1988), although perceptual judgments are unaffected. Further evidence of the parietal system’s involvement in motor capacities can be seen in visual neglect, most commonly arising from right-side lesions to the posterior parietal cortex. This condition is not always restricted to a perceptual or attentional deficit but may also be characterized along a perceptuomotor dimension, with some patients exhibiting a deficit restricted primarily to performing motor actions in the affected region of space (see Bisiach, 1993, for a review). This characteristic is also borne out by the lesion studies of Rizzolatti, Gentilucci, and Matelli (1985), who found that the neural circuits controlling motor actions in specific regions of space (e.g., reaching in the space surrounding the body or orienting to stimuli in the far space) were also endowed with their own mechanisms of visual attention.

Physiological research also highlights the parietal system’s role in coding action-related information as well as visuospatial information. Populations of cells in the parietal cortex code for both the position of stimuli in head-centered space, if not also in other reference frames, as well as for the direction of forthcoming movement (Andersen, 1987). Furthermore, more than directional information is represented here, with many cells being responsive to the relation between visual stimuli and the hand shapes required to grasp them (Sakata, Taira, Mine, & Murata, 1992; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990).

In the motor areas a similar integration between visual and motor processing is apparent. Cells in this area have both sensory and motor properties, and the motor cortex itself is far from being merely a muscle controller—only a fraction of its cells are directly related to muscle activation (Georgopoulos, 1991, 1992; Requin, Riehle, & Seal, 1993). Multiple representations of stimulus and response properties exist in both parietal and motor areas. These are both graded with respect to their sensitivity to visual or motor components of the stimulus or response and also with respect to the

level at which information is represented. This can be seen in the representation of forthcoming movement direction by neuronal population codes (Georgopoulos, Schwartz, & Kettner, 1986). The sensitivity of a neuronal population code for the direction of movement to externally applied forces (load conditions) is one such measure of abstraction, because the muscle forces required to produce the same trajectory change depending on the external loads applied. Population codes insensitive to external loads can be said to represent the direction of movement at a relatively abstract, kinematic level, because their response properties reflect the direction of movement irrespective of the actual muscle commands necessary to implement it. Conversely, populations sensitive to load conditions represent the movement at a less abstract level, one concerned with the dynamic control of the muscle forces required to bring it about. Load sensitivity forms a continuum, with populations less sensitive being more common in the parietal cortex and those most sensitive being more common in the primary motor cortex (Kalaska & Crammond, 1992). Each area, however, contains codes at all levels of load sensitivity, and the primary motor cortex, the area closest to the implementation of motor commands, contains a large proportion of cells coding direction of movement at an abstract kinematic level (Alexander & Crutcher, 1990b; Georgopoulos, 1991).

Even when the direction of movement of the limb is dissociated from that of the response, many cells in the motor areas remain sensitive to the visual direction of the response irrespective of the direction of limb movement needed to achieve this. In a study by Alexander and Crutcher (1990a), monkeys were trained to move a cursor to a visual target by a single joint movement of the forelimb. This movement was carried out in two conditions, one in which the left or right movement of the forelimb resulted in a corresponding left or right movement of the cursor and the other in which the cursor moved in the direction opposite that of the forelimb. More than a third of the cells in the motor cortex, supplementary motor area, and putamen remained sensitive to the direction of movement of the visual cursor, rather than that of the limb, in both conditions. Not only does this illustrate the abstract nature of the response properties of a large proportion of the cells in the motor areas but it also highlights their sensitivity to visual aspects of the response rather than purely implementational properties (in the sense of muscle commands).

Most physiological studies of stimulus and response coding have been carried out on explicit goal-directed actions. Animals have been trained to make motor responses to a target stimulus. The degree to which action codes are activated automatically by visual stimuli is of course very difficult to assess, because it requires correlating neural activity with an event that need not occur. Nonetheless, the organization of the visual and motor apparatus provides ample opportunity for the partial representation of visual and motor codes in the absence of an existing intention to act. Indeed, in humans, when frontal cortical control is lost through damage, “utilization behavior” can arise in which visual stimuli automatically elicit motor responses such as reaching and grasping (Lhermite, 1983). This suggests that

motor acts are controlled, in part, by the active suppression and subsequent selection and tuning of already existing sensorimotor connections (MacKay & Crammond, 1989).

Interpreting physiological data as evidence of specific representational roles is highly problematic—especially so in the case of single cell recordings. There is no reason in principle, after all, why the response properties of cells embedded in as complex a network as the brain should equate with their representational role (see, e.g., Robinson, 1992). Performance measures are therefore extremely important in establishing any proposal concerning the way information is processed. In the next section we describe a behavioral paradigm ideally suited to examining automatic response processes and one in which some evidence already exists for the automatic activation of action codes, albeit at relatively abstract levels.

Stimulus–Response Compatibility

The stimulus–response compatibility (SRC) paradigm has participants make speeded choice responses based on the value of a stimulus property. SRC refers to the relative advantage of certain stimulus–response mappings over others (see Alluisi & Warm, 1990, for a review). Whenever there is a relationship between properties of the stimulus and response sets, the conditions for obtaining SRC effects are present. A robust finding is that mappings that match properties that the stimulus and response share are faster than mappings that do not match such properties. In the simplest case, assigning left responses to left stimuli and right responses to right stimuli results in shorter response latencies than does the reverse mapping. In this case both stimuli and responses share a location dimension that facilitates responding when the mapping rule is congruent. Where spatial compatibility is concerned, it is not the absolute position of the responses in relation to the stimuli that is important, but their relative positions (Umiltà & Nicoletti, 1990). Furthermore, it is the position of the response locations rather than the effectors used to make them that has been found to be important in obtaining SRC effects. Congruent mappings between stimulus and response locations are still faster than incongruent mappings when the hands are crossed, and thus the left response is produced by the right hand and vice versa (Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977).

Because of the abstract nature of the properties associated with compatibility effects, they are generally assumed to operate on mental codes of the stimulus and response features (see Proctor & Reeve, 1990) rather than on any physical correspondence between the two. An exception can be found in the ecological approach taken by Michaels (1988, 1993), who proposed that many compatibility effects could be based on the detection of affordances—especially in stimulus–response environments containing relatively rich optical information. Even within abstract SRC arrangements, the action system has been proposed to influence what constitutes compatible and incompatible stimulus–response mappings. Bauer and Miller (1982), for example, found that the preferred mappings between orthogonal

vertical and horizontal stimulus and response locations were best predicted by different rotational preferences for the left and right hands (but see Weeks & Proctor, 1990, for an alternative explanation). In fact, the preferences for particular mappings between up–down stimuli and left–right responses have been shown to be highly sensitive to the actual distance of the hands from the body midline, which implies that the state of the action system, as well as its organization, can influence the compatibility relations that emerge (Michaels, 1989). In a similar vein, Tipper, Lortie, and Baylis (1992) showed that when participants perform actual reaching movements to three-dimensional targets in the presence of distractor targets, the interference effects produced by the distractors are best accounted for by a hand-centered attentional framework. Thus, the way the visual world is represented is to an extent dependent on the use to which the visual information present in it is being put.

Kornblum (1994; Kornblum, Hasbroucq, & Osman 1990) proposed that the required relationship between stimulus and response properties for SRC effects to occur could be characterized by the notion of dimensional overlap. Dimensional overlap exists between response and stimulus sets whenever they share a perceptual, conceptual, or structural property. Thus, if stimuli and responses can both be characterized along a spatial dimension such as a left–right location, then compatibility effects can be produced by the assignment of congruent or incongruent mappings of stimulus location to response location. It is important to note that the effect of dimensional overlap is not restricted to the stimulus property that is relevant for response determination, although the size of the effect produced is generally larger when the overlap occurs on the relevant dimension (Kornblum & Lee, 1995). Particular attention has been paid to the effect of an irrelevant spatial dimension (usually simply location), known as the *Simon effect* (Simon, 1969). The Simon effect is similar to Stroop-like interference effects except that the overlap occurs between stimulus and response dimensions rather than between two dimensions of the stimulus itself (Kornblum, 1994; Kornblum & Lee, 1995). Hasbroucq and Guiard (1991) proposed that the Simon effect was due to stimulus congruence or incongruence and as such occurred at the stimulus identification stage rather than at the response selection stage, which would thereby render the effect a spatial variant of the Stroop task. Even when the only congruence occurred across stimulus and response features (rather than stimulus–stimulus features as is the case in the Stroop task proper), Hasbroucq and Guiard argued that the task constraints led to the formation of an additional stimulus code, based on the response it signified, and that this formed the basis of stimulus–stimulus congruence effects. Most other accounts place the Simon effect at the response selection stage, resulting either from the automatic activation of a response code (Kornblum et al., 1990) or from the automatic application of the translation rule for the relevant stimulus dimension to the irrelevant dimension (Lu & Proctor, 1994).

Recent evidence favors the former account. Psychophysiological studies using lateralized event-related potentials (Eimer, 1995) and single unit recordings (Requin & Riehle,

1995) have shown that irrelevant location information automatically induces a (spatially congruent) response code in both compatible and incompatible trials. This location code appears to be formed relatively fast and to decay automatically, a consequence of which is that factors affecting the speed with which the relevant (nonlocation) dimension is processed have a strong influence on the magnitude of the Simon effect (Hommel, 1994a, 1994b). The automaticity of location-dependent response codes is further attested to by the fact that they exert an influence even when the forthcoming response is known with certainty but must be delayed until a go/no-go signal is presented in compatible or incompatible locations (Hommel, 1995). Eimer, Hommel, and Prinz (1995) suggested that there is a direct, and partially independent, route from the perception of the stimulus to the formation of a response code, which operates in parallel to the indirect route involving the translation of the relevant stimulus feature to the response code (see also Riddoch, Humphreys, & Price, 1989, and Rumiat & Humphreys, 1998, for evidence of a direct route from vision to action).

The evidence from research into SRC supports the view that certain action-related properties of a stimulus generate automatic response codes, at least with respect to information about spatial location. Although of primary importance, location is only one of many object properties that are relevant to potential actions. Size, shape, and orientation all contribute to an object's affordances and are also processed, together with spatial location, in the dorsal visual pathway. Cells responsive to quite specific action-related properties of objects, such as grip type and stimulus orientation, can be found in the parietal and motor areas. The question we are interested in is the extent to which partial information about action-relevant properties such as these is also represented automatically during the perception of an object. Thus when one reaches and grasps an object, is the information about the required preshaping of the hand, for example, produced from scratch at the moment the intention is formed, or is some of this information already represented? This idea is similar to the position put forward by Goldberg and Seagraves (1987) with reference to the planning of eye movements. These authors provided evidence that eye movement plans in the monkey are selected from an already existing repertoire of motor signals, rather than being generated anew. Such a repertoire of potential movements is generated automatically by visual stimuli. Although directing attention may be a special case, in the sense that one expects certain visual stimuli automatically to evoke attentional orienting mechanisms, the important point is that such selection was found to operate on candidate motor plans rather than on candidate visual stimuli. Selecting movement plans from an already existing repertoire of motor signals has advantages both in terms of execution time and, perhaps more important, in terms of making available the actual actions possible in a given environment—information that must be present if the intentions one forms are to relate to the world.

We use the term *affordance* to refer to the motor patterns whose representation visual objects and their properties give rise to, both during explicit goal-directed acts (see Jean-

nerod, 1994, for a similar use of affordances) as well as, we argue, before explicit intentions have been formed. Although this is a representational account of affordances, and therefore very different from the use of the term in the ecological sense, it nonetheless has its basis in a similar emphasis of the intimate link between perception and action.

Experiments

Our aim in the experiments reported here was to use an SRC paradigm to explore the hypothesis that more than location-based response codes could be activated automatically by visual objects—in particular, that the actions the object affords are automatically potentiated. Most stimuli used in SRC research have no natural significance for action—they vary on a few abstract dimensions such as color and location. It is perhaps not surprising, therefore, that compatibility effects appear to take place at a relatively abstract level. In agreement with Michaels (1988, 1993), we assume that our everyday actions are governed by nonabstract, meaningful relations between the visual environment and the action systems of the observer. The generation of response codes based on information about possible actions cannot take place unless the stimuli themselves have some significance for action. We used, therefore, photographs of real objects as stimuli because these have spatial properties whose variation affects the actions that can be directed toward them. Behavioral evidence indicates that object attributes that determine the type of grasp used to pick them up produce compatibility effects on movement initiation time when the task is to reach and grasp the object with a hand shape determined by the color of the object (Klatzky, Fikes, & Pelligrino, 1995). In those experiments, however, the reaching-and-grasping response was actually called for. They thus provide evidence for the representation of hand shape information prior to movement execution, but not for its automatic activation.

In the first experiment we examined the relation between an object's orientation and the hand most suited to perform a reach-and-grasp movement. A centrally placed graspable object, such as a saucepan, can be seen to be most suited to a right-handed grasp when the handle is oriented toward the right side, and vice versa with regard to a left-handed grasp. For objects without protruding handles, such as an iron or a knife, the handle is aligned with the major axis of the object. In this case the object is most compatible with a grasp by the hand toward which this axis is oriented. If the representation of a visual object includes action components, such as the preferential activation of the hand most suited to perform a reach-and-grasp movement, then one might expect this activation to facilitate simple keypress responses carried out by the congruent hand and, conversely, to interfere with those same responses carried out by the incongruent hand. This was the rationale behind Experiment 1. We chose an object property other than horizontal orientation as the criterion for selecting the hand of response—in this case, object inversion. Thus, left-right object orientation, and the grasp compatibility that arises from it, was irrelevant to the determination of the response but was nonetheless predicted

to affect the speed with which the response was selected and executed. It is important to point out that hand dominance may override the effect of horizontal object orientation in many instances of everyday prehension. Thus one may often reach for and grasp an object with the dominant hand even though its orientation is not maximally compatible with a grasp made by that hand. This, however, does not affect the conclusions that can be drawn from the present study. Even though in instances of everyday prehension, hand selection will rarely be exclusively determined by object orientation, nonetheless, given a particular hand used, the horizontal orientation makes it more or less compatible with that hand. In Experiment 1 the horizontal orientation of the object could be said to be more or less compatible with the cued hand (whether or not the cued hand would have been used to grasp the object in real life). Thus, under the hypothesis put forward about action potentiation, compatibility effects would be expected from the relation between the left-right orientation of the object and the hand used to make the response, the latter being cued by object inversion.

Experiment 1

Method

Participants. Thirty students took part in the experiment. All were enrolled at the University of Plymouth and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. All except 2 participants reported that they were right-handed.

Apparatus and materials. Black and white transparencies of 22 graspable household objects made up the stimulus set (see Appendix A for a list of objects used). All the objects were capable of being grasped and manipulated by one hand and were photographed in two horizontal orientations (one compatible with a right-hand grasp, the other with a left-hand grasp) and two vertical orientations (upright and inverted). There were thus $22 \times 2 \times 2 = 88$ slides that were back-projected onto a translucent screen (46×46 cm) from two Kodak carousel random access projectors, modified to allow millisecond shutter control. Examples of the stimuli are shown in Figure 1. The participant was seated with his or her head 45 cm in front of the screen and with the index finger of each hand resting on two response buttons 30 cm apart and 15 cm in front of the screen. The objects were photographed so as to appear as if they were resting on the table at the position of the screen, at approximately their actual size, at a distance of 50 cm. They subtended visual angles of between 11° and 18° .

Design and procedure. The experiment consisted of two blocks of 176 trials in which each object appeared twice in each horizontal and vertical orientation. Participants were instructed to make push-button responses with the left or right hand depending on whether the object was upright or inverted. The actual mapping of response hand to object inversion was blocked and pseudorandomized so that an equal number of participants received each mapping in the first block. For most objects, whether the object was upright or inverted needed no definition. In the case of objects such as a knife or saw, participants were told that upside down or upright was defined with regard to the object's normal use. Such objects were thus photographed with the blade at right angles to the resting surface, rather than lying flat, and were upside down when the blade or teeth were pointing up rather than down. Participants experienced no difficulty in understanding this definition of inver-

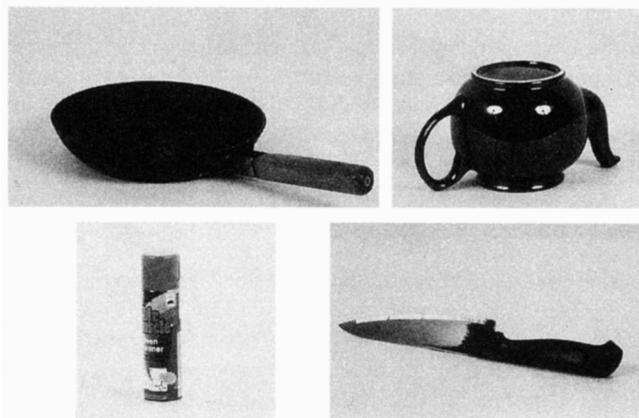


Figure 1. Examples of the stimuli used in the experiments. Experiments 1 and 2: right orientation, upright (frying pan); left orientation, inverted (teapot). Experiment 3: anticlockwise wrist rotation compatibility, inverted (knife); clockwise wrist rotation compatibility, upright (aerosol can).

sion. The left-right horizontal orientation of the object was irrelevant to the response. Participants were instructed to respond as fast as possible whilst maintaining accuracy. Slide order was randomized for each participant, and the experiment was run, and response latencies recorded, on an Acorn Archimedes computer. Each participant received 20 practice trials before each block. A trial began with the appearance of an object on the screen and ended when a response had been made or 3 s had elapsed. The objects remained in view until a response was made. There was a 4-s delay between the end of one trial and the beginning of the next. Participants were not given feedback on response latencies, but errors were immediately followed by a short tone from the computer.

Results

Response times. Two participants were removed from the analysis because their error rates exceeded 10%. Error trials and reaction times more than 2 *SDs* from the condition means were excluded from the analysis. The means for each object in each of the eight conditions were computed for each participant. For the participants analysis, condition means were obtained by averaging across objects, and for the materials analysis they were obtained by averaging across participants. An analysis of variance (ANOVA) was conducted on the participant data with the independent variables of mapping (right-hand-upright/left-hand-inverted or left-hand-upright/right-hand-inverted [RH-UP and LH-UP, respectively]), response (left hand or right hand), and object orientation (left or right). There was a significant main effect of response mapping. Responses in the RH-UP mapping ($M = 616.68$ ms) were faster than responses in the LH-UP mapping ($M = 650.35$ ms), $F(1, 27) = 8.61, p < .01$. The only other significant effects were the two-way interactions between response mapping and hand of response and between hand of response and left-right object orientation. The interaction between mapping and hand of response is easily interpretable as an effect of object inversion. Right-hand responses in the RH-UP

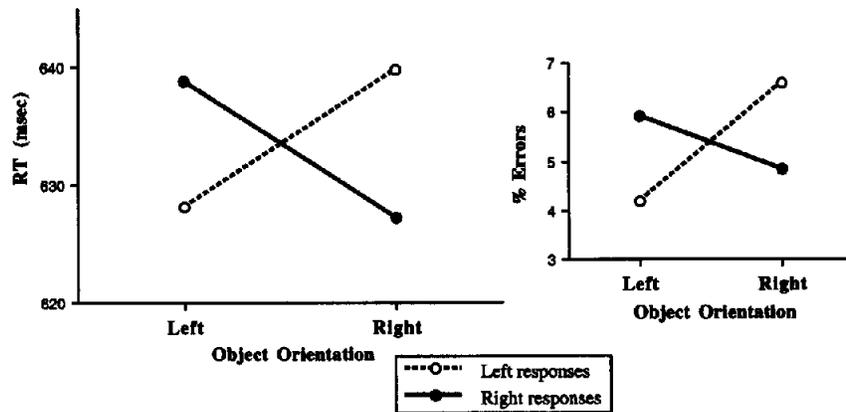


Figure 2. Mean reaction times (RTs) and error rates for Experiment 1 as a function of left–right object orientation and response (left or right hand).

mapping ($M = 607.7$ ms) tended to be faster than left-hand responses ($M = 625.6$ ms), whereas in the LH–UP mapping, left-hand responses ($M = 642.3$ ms) tended to be faster than right-hand responses ($M = 658.4$ ms), $F(1, 27) = 16.8$, $p < .001$. Because object inversion can be derived from the combination of hand of response and mapping rule it can easily be seen that the above results reflect the fact that responses to upright objects were, on average, 17 ms faster than responses to inverted objects. This result is to be expected because to determine whether an object is upright or inverted it must be recognized, and this will be faster for a canonical orientation.

The two-way interaction between object orientation and hand of response is the most interesting result. This interaction is displayed in Figure 2. Right-hand responses were faster when the irrelevant orientation of the object was also to the right ($M = 627.3$ ms) rather than to the left ($M = 638.8$ ms). Similarly, left-hand responses were faster when the orientation of the object was also to the left ($M = 628.2$ ms) rather than to the right ($M = 639.8$ ms), $F(1, 27) = 11.85$, $p < .005$. Pairwise comparisons (Newman–Keuls) showed both of these differences to be significant. For right-hand responses, $q(2, 27) = 3.42$, $p < .05$, and for left-hand responses $q(2, 27) = 3.45$, $p < .05$, $MSE = 634.0$.

Errors. Analysis of percentage error rates revealed a pattern of results similar to that for response times (see Figure 2), although the effect of mapping and the mapping by response interaction were not significant. The interaction between response and horizontal object orientation was significant, $F(1, 27) = 13.51$, $p < .005$. In addition, there was a small but significant effect of object orientation, with objects oriented to the left (left-hand grasp compatibility) producing fewer errors ($M = 5.05$) than objects oriented to the right ($M = 5.70$), $F(1, 27) = 4.76$, $p < .05$. The pattern of errors indicated the absence of any speed–accuracy trade-offs.

Materials analysis. A materials analysis on response times with objects as a random factor and condition means averaged over participants yielded the same pattern of results as the participants analysis. The RH–UP mapping

produced faster responses ($M = 618.2$ ms) than the LH–UP mapping ($M = 649.3$ ms), $F(1, 21) = 64.63$, $p < .001$. Right-hand responses in the RH–UP mapping ($M = 609.9$ ms) were faster than left-hand responses ($M = 626.5$ ms), whereas in the LH–UP mapping, left-hand responses ($M = 640.8$ ms) were faster than right-hand responses ($M = 657.7$ ms), $F(1, 21) = 6.39$, $p < .05$. Again, the two-way interaction between object orientation and hand of response was significant, with right-hand responses being executed faster when the object was oriented to the right ($M = 627.5$ ms) than when it was oriented to the left ($M = 640.1$ ms), whereas left-hand responses were faster when the object was oriented to the left ($M = 629.3$ ms) than when it was oriented to the right ($M = 638.0$ ms), $F(1, 21) = 22.79$, $p < .001$.

The stimuli used in this experiment constitute only one sample of the population of graspable objects whose horizontal orientation can affect the ease with which they are grasped by a particular hand. They were thus treated as a random factor. In order to provide a test of the ability of the interaction between response hand and object orientation to generalize to a new sample of participants and objects simultaneously, we computed $\text{Min } F'$ (see Clark, 1973). The result obtained, $\text{Min } F'(1, 46) = 7.79$, $p < .01$, was highly significant, which suggests that this effect is unlikely to be restricted to the particular objects used in the experiment.

Discussion

The first experiment showed that the left–right orientation of common graspable objects had a significant effect on the speed with which a particular hand made a simple push-button response, even though the horizontal object orientation was irrelevant to response determination. The orientations of the objects were chosen so as to make them

¹Min F' provides a conservative test of the ability of an effect to generalize simultaneously to a new sample of participants and objects. Exact F ratios cannot be obtained with participants and objects as random factors in a single analysis. The formula for Min F' is given in Appendix B.

preferentially compatible with a reach-and-grasp movement by the left or right hand. When the required response, determined by the mapping condition and the inversion of the object, was with the right hand, response times were shorter, and errors fewer, when the object's horizontal orientation was also compatible with a right-hand reach-and-grasp movement. Similarly, left-hand responses were faster when the object was compatible with a left-hand grasp. This supports the proposal that certain action-related information—in this case the hand most suited to grasp the object—is represented automatically when the object is viewed in the peripersonal space.

The data, do not, of course, rule out other explanations. In particular, it is possible that object orientation was automatically assigned an abstract spatial response code and that this was the basis for the observed effects. In this case, the results could be interpreted as a Simon effect of an irrelevant spatial stimulus dimension, consistent with Kornblum et al.'s (1990) dimensional overlap model of SRC. In their terminology, the experiment would be classified as a *Type 3 ensemble*. A Type 3 ensemble has dimensional overlap between the irrelevant stimulus dimension (object orientation in this experiment) and the response, and no dimensional overlap between the relevant stimulus dimension (object inversion here) and the response. In fact, the main effect of response mapping (right-hand responses to upright objects and left-hand responses to inverted objects were on average 34 ms faster than the reverse mapping) does appear to be a standard SRC effect. Although here there was no overlap between the stimulus and response dimensions, Weeks and Proctor (1990) have proposed a salient features model of SRC effects to account for the existence of compatibility relations between such orthogonal dimensions. In this account, response times will be shortest when the required mapping matches the relative salience of the stimulus and response dimensions. This would account for the mapping effect observed here, given that an upright object and a right-hand response represent the salient features of the stimulus and response sets, respectively. The abstract nature of such saliency codes is necessitated by the lack of any physical overlap between the two dimensions.

It is possible that horizontal object orientation, however, is also coded as "left" or "right," thereby overlapping with the response dimension. If the results of previous SRC research reflect cognitive mechanisms capable of generalizing to more complex stimuli, then such an abstract level of coding may be entering into the observed effect. However, this does not rule out the possibility that response codes at a less abstract level are also generated automatically when the stimuli are meaningful and vary along dimensions important in determining the way we interact with them. The properties of a visual object represented by the (dorsal) visual system are precisely those needed to successfully prepare and guide actions. It would seem likely, therefore, that any codes generated automatically by a visual object would contain information about the relation between the object and the motor system of the observer.

One way of clarifying the relative contributions of abstract spatial coding of orientation along a left-right

dimension and the automatic activation of a response code based on the hand most suitable for grasping the object would be to conduct a unimanual version of Experiment 1. The importance of relative, rather than absolute, spatial coding in obtaining standard compatibility effects is well attested to in the literature (Proctor & Reeve, 1990; Umiltà & Nicoletti, 1990). If object orientation being coded along an abstract left-right dimension was responsible for the automatic generation of a left-right response code, then the same pattern of results should be obtained when the response is a left-right finger press of a single hand. (Comparing the effect of a relevant location dimension in bimanual and unimanual SRC tasks, Shulman and McConkie, 1973, found that the compatible mapping produced an advantage of the same magnitude in both tasks.) If, on the other hand, the effect was produced solely by the activation of a response based on the hand most suitable for grasping the object, then the effect should be much smaller or absent in a unimanual condition. We conducted Experiment 2 to find out which result would obtain.

Experiment 2

The effect of object orientation on response latencies in Experiment 1 is consistent with an account based on the automatic activation of a response from the abstract left-right coding of the object's horizontal orientation as well as with one based on the object's grasp compatibility. If the effect is due solely to the former, then dissociating the left-right response positions from the effectors used to implement them should have little effect on the pattern of results. Experiment 2 was designed to provide a means to compare the relative contributions of abstract coding and action potentiation to the effect observed in Experiment 1. This assumes that left-right object orientation has no preferential effect on the actions that can be carried out by the index and middle fingers of the right hand.

Method

Participants. Thirty students at the University of Plymouth took part in the experiment. All had normal or corrected-to-normal vision and had not participated in the first experiment. They were paid £3.00 for participating. All participants reported being right-handed.

Apparatus and materials. The stimulus materials were identical to those used in Experiment 1 except that two objects (eight slides) were removed from the set because one slide had been damaged. A total of eight slides had to be removed to keep the stimulus set balanced. This meant that the total number of trials per participant was reduced from 176 to 160. The only other difference was that responses were executed on a single device operated by the index (left response) and middle (right response) fingers of the right hand. The two response buttons were 2.5 cm apart and positioned centrally 15 cm in front of the viewing screen.

Procedure. The procedure was identical to that of the first experiment except that participants were instructed to make left-right responses with the index and middle fingers of their right hands.

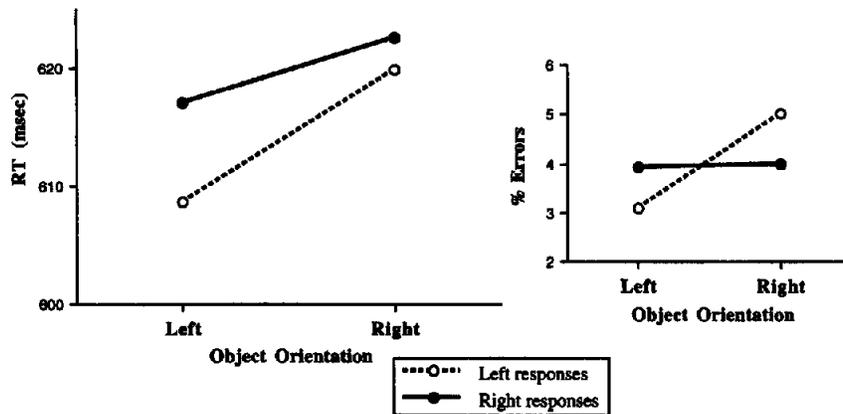


Figure 3. Mean reaction times (RTs) and error rates for Experiment 2 as a function of left–right object orientation and response (left or right finger).

Results

Response times. The data from 3 subjects were not analyzed because their error rates exceeded 10%. Error trials and reaction times more than 2 *SDs* from the condition means were excluded from the analysis. For the rest, mean response times for each object in each condition were computed. As in Experiment 1, condition means for the participants analysis were computed by averaging over objects, whilst for the materials analysis they were computed by averaging over participants. An ANOVA was performed on the participant data with mapping, object orientation, and response (left or right finger) as independent variables. There was a significant main effect of object orientation. Responses to objects oriented to the left were faster ($M = 612.9$ ms) than responses to objects oriented to the right ($M = 621.3$ ms), $F(1, 26) = 4.73, p < .05$. As in Experiment 1, there was a significant two-way interaction between mapping and response, best understood as a speed advantage for upright objects. In the RF–UP (right-finger–upright), mapping, right (middle) finger responses ($M = 612.1$ ms) were faster than left (index) finger responses ($M = 621.6$ ms), whereas in the LF–UP (left-finger–upright) mapping, left-finger responses ($M = 607.1$ ms) were faster than right-finger responses ($M = 627.6$ ms), $F(1, 26) = 13.61, p = .001$. This two-way interaction simply reflects the fact that responses to upright objects were on average 15 ms faster than responses to inverted objects, as observed in Experiment 1. Of most interest, however, is the two-way interaction between response and horizontal object orientation. The pattern of means was quite different from that observed in Experiment 1 (see Figure 3). Right responses to objects oriented to the left ($M = 617.1$ ms) were actually slightly faster than the same responses to objects oriented to the right ($M = 622.6$ ms). For left responses, objects oriented to the left tended to be responded to faster ($M = 608.7$ ms) than objects oriented to the right ($M = 620.0$ ms). This two-way interaction was not significant,² $F(1, 26) = 1.17, p = .29$.

Error rates. The pattern of error rates was similar to that for response times (see Figure 3). An ANOVA on percentage

error rates found a single significant main effect of left–right object orientation. Participants made fewer errors to objects oriented to the left ($M = 3.52$) than to objects oriented to the right ($M = 4.49$), $F(1, 26) = 8.82, p < .01$.

Materials analysis. An ANOVA with objects as a random factor and condition means obtained by averaging over participants showed the same pattern of results as that observed in the participants analysis. The effect of object orientation was significant, with left-oriented objects ($M = 620.9$ ms) being responded to faster than right-oriented objects ($M = 612.2$ ms), $F(1, 19) = 4.38, p = .05$. The interaction between response and mapping was significant and identical in form to that observed in the participants analysis, $F(1, 19) = 5.94, p < .05$. Again, the interaction of most interest, that between response and left–right object orientation, was not significant, $F(1, 19) = 0.53, p = .476$.

As expected from the results of both the participants and materials analyses, computation of Min F' gave an insignificant result: Min $F'(1, 35) = 0.36$, critical value at $\alpha (.05) = 4.13$.

Experiments 1 and 2 compared. The main purpose of Experiment 2 was to help determine the extent to which the compatibility effect observed in Experiment 1 could be attributed to graspability rather than to the abstract coding of object orientation into left and right codes congruent or incongruent with the left–right response locations. The critical comparison is between the Response \times Object Orientation interactions in the two experiments. This can be seen from a comparison of Figures 2 and 3. In order to test whether these interactions differed significantly, we computed a further ANOVA on the data from both experiments

²In an analysis using medians rather than means we did in fact find a significant result for this effect. Its significance was much smaller than in Experiment 1, and it was not present for the materials analysis. Use of untrimmed means and a straight 1,000-ms cutoff produced the same results as those reported in the text. (For a discussion of the problems of finding the right measure for reducing the effect of outliers in reaction time data, see Ratcliff, 1993.)

with experiment (Experiment 1 or 2) as a between-subjects factor. To achieve balanced nesting of participants within experiments, we removed 1 randomly selected participant's data from the data for Experiment 1. Of most importance was the fact that the difference between the Simon effect in the two experiments, corresponding to the three-way interaction between object orientation, response, and experiment, was significant, $F(1, 52) = 4.74, p < .05$. This gives statistical confirmation to the differences in the Simon effects observable in Figures 2 and 3. In addition, the pooled data also showed a significant overall Simon effect of response and object orientation. Overall, right responses to right-oriented stimuli ($M = 622.5$ ms), tended to be executed faster than to right responses left-oriented stimuli ($M = 626.2$ ms), whereas left responses tended to be faster to left-oriented stimuli ($M = 616.3$ ms) than to right-oriented stimuli ($M = 627.8$ ms), $F(1, 52) = 12.28, p = .001$. However, in light of the significant three-way interaction and the separate analyses for Experiments 1 and 2, this result can be seen to be mainly attributable to the highly significant effect in Experiment 1. The combined data also revealed a significant main effect of mapping, with the assignment of right responses to upright stimuli (R-UP, $M = 615.2$ ms) producing faster response times than the reverse mapping (L-UP, $M = 631.21$ ms), $F(1, 52) = 4.75, p < .05$. This effect interacted with experiment, which showed that the main effect of mapping was in fact almost completely attributable to an advantage for the R-UP mapping ($M = 613.6$ ms) over the L-UP mapping ($M = 645.1$ ms) in Experiment 1, there being little preference for either mapping in Experiment 2 (616.8 vs 617.3 ms), $F(1, 52) = 4.47, p < .05$. As expected, the combined data showed a significant interaction between mapping and response, observed in both experiments, which we attribute to a consistent speed advantage for upright stimuli, $F(1, 52) = 28.73, p < .0001$.

Discussion

The most important finding of Experiment 2 was the fact that a significant interaction between left-right object orientation and left-right response was not obtained when the responses were executed by a single hand. As mentioned in Footnote 2, a small effect, with a pattern identical to that in Figure 3, was observed when medians were used (although only in the analysis by participants). However, the robustness of any such effect, and thus the relation between response location and left-right object orientation, is markedly less than that of the result obtained when the response was executed bimanually, as a comparison of Figures 2 and 3 and the results of the combined ANOVA make clear. There seems to be no compatibility effect of left-right object orientation when the relation between left-right object orientation and the spatial position of the responses is only relative. Both types of coding (of the actions the object potentiates and the abstract left-right coding of object orientation) are not mutually exclusive, of course, but the results suggest that the compatibility effect observed in Experiment 1 is unlikely to be attributable to the abstract

coding of object orientation. Instead, we believe the results are consistent with the view that grasp compatibility underlies the effect observed between horizontal object orientation and hand of response.

The fact that the (irrelevant) left-right orientation of a selection of natural objects produces compatibility effects further supports the view that it is the relevance of this property for action that underlies the left-right coding. The visual properties that define whether the object is oriented to the left or the right vary widely from object to object, making the formation of an automatic left-right stimulus code unlikely (contrast this with the typical Simon paradigm in which it is the spatial location of the stimulus which gives rise to left-right codes). The absence of a compatibility effect in the unimanual condition of Experiment 2 supports this view. How then might such binary left-right codes have arisen in Experiment 1 from such a complex and varying stimulus property? An explanation that makes sense is that the coding into left and right takes place not at the level of the stimulus, but at the level of the response. Rather than object orientation automatically generating a left-right code by virtue of the visual properties of the object (in which case one would expect compatibility effects in Experiment 2), it is the affordance for grasping by a particular hand that gives rise to the binary left-right distinction. This explanation supports the view that the actual left or right code generated by the object consists of the partial activation of motor patterns associated with the compatible hand, because it is only at this level that the left-right distinction is apparent. That this takes place for an irrelevant stimulus property and during a task in which no actual reach-and-grasp movements are required supports the proposal, outlined in the introduction, that the actions afforded by an object are intrinsic to its representation.

In Experiments 1 and 2 we manipulated the left-right orientation of an object in order to affect its grasp compatibility. Choosing which hand with which to reach for an object is only one aspect of a process that results in the object's being grasped. Orientation, object size, and the position of the opposition space in the object all influence the way the hand must approach the object. To successfully grasp an object, the hand must be rotated to bring the fingers in line with the opposition space (Arbib, 1990; Iberall, Bingham, & Arbib, 1986; Jeannerod, 1981; Jeannerod, Paulignan, Mackenzie, & Marteniuk, 1992). In Experiment 3 we used the wrist rotation component of reaching and grasping to further examine the response codes activated by visual objects.

Experiment 3

Categories of objects can be formed on the basis of the way the wrist needs to rotate from a neutral orientation in order to form a stable grasp. If the initial orientation of the wrist is such that the base of the thumb is aligned at the 11 o'clock position, tall cylindrical objects require a clockwise wrist rotation to bring the hand into alignment for a suitable grasp. The reverse direction of rotation is required for horizontally oriented objects or for any object that is small relative to the hand. The 11 o'clock position of the thumb is

neutral in the sense that the wrist has a natural tendency to return to this orientation (see Rosenbaum et al., 1990). Examples of the two directions of wrist rotation are reaching and grasping an upright wine bottle (clockwise rotation) and grasping a knife resting on a table at approximately right angles to the line of sight, with the handle to the right (anticlockwise rotation). If the wrist of one's right hand is positioned in front of one, with the thumb aligned at the 11 o'clock position, in order to reach for and grasp the wine bottle the wrist must rotate in a clockwise direction to bring the fingers and thumb into the correct position to achieve a stable grasp. In contrast, if one were to reach for and grasp the knife, the wrist would need to rotate in an anticlockwise direction in order to achieve the grasp. In this experiment we used two sets of objects—one set required a clockwise wrist rotation from the neutral start position to achieve a stable grasp, and the other set required an anticlockwise rotation (see Appendix C for a list of objects used). Unlike the situation in the previous two experiments, object orientation was not manipulated. Many of the objects used, such as bottles or jars, did not possess a left-right horizontal orientation at all. Those that did, such as a jug or a spoon, were always oriented with the handle to the right (because responses were always executed by the right hand). The compatibility relation was determined by the direction of wrist rotation needed to grasp the object and the direction of rotation cued by the inversion of the object³ given one of the two mapping rules.

Method

Participants. Thirty-four students at the University of Plymouth took part in the experiment. All were naive as to the purpose of the experiment, were right-handed by self-report, and had normal or corrected-to-normal vision. Participants were paid £3.00 or received course credit for their participation.

Apparatus and materials. These were the same as in Experiments 1 and 2 with the following exceptions. The stimulus set consisted of colored slides of 40 objects, 20 compatible with a clockwise wrist rotation and 20 with an anticlockwise rotation (see Figure 1 and Appendix C). These were photographed in both upright and inverted positions but in a single orientation (as described above). Responses consisted of a small clockwise or anticlockwise wrist rotation from the neutral starting position. Responses, and start position of the wrist, were monitored by a small device taped to the underside of the wrist of the participant's right arm. This consisted of two pairs of mercury tilt switches connected to an Archimedes Acorn computer. One set was finely tuned about the correct start position and caused a signal to be sent if the wrist orientation diverged more than $\pm 3^\circ$ from this position. The other set, used to record the response, was less finely tuned and required a wrist rotation greater than $\pm 9^\circ$ to trigger a response. Participants sat facing the screen with their right arms resting on the arm rest. Their right wrists overhung the end of the arm rest so that the response device was free to be rotated with their wrists. Participants sat facing the screen with their wrists aligned with the right-hand edge and the tips of their fingers positioned 20 cm from the screen.

Procedure. The experiment consisted of two blocks of 160 trials in which each object was presented twice in both upright and inverted conditions. Response mapping was blocked and pseudorandomized so that an equal number of participants received each

mapping condition in the first block. The two response mappings consisted of making a clockwise wrist rotation if the object was upright and an anticlockwise wrist rotation if the object was inverted, and vice versa. Participants were instructed to respond as fast as possible whilst maintaining accuracy. Each participant received 20 practice trials per block. The position of the wrist was monitored so that trials would not proceed until the wrist was within $\pm 3^\circ$ of the correct starting position. If the wrist was outside these limits, the computer emitted a rapid beeping that was terminated when the wrist was correctly aligned. A slide was projected after 2 s if the wrist maintained the correct starting position. The slide remained in view until a response was made or 3 s had elapsed, after which the next trial began automatically with a delay of 2 s. Thus if the wrist returned to the correct position after a trial, the intertrial interval was 4 s. Most participants experienced no difficulty in rapidly returning their wrists to the correct start position.

Results

Response times. The average error rate for this experiment was considerably higher than the error rates in the previous experiments, and we used a 12.5% error cutoff to avoid discarding an excessive amount of data. This resulted in the removal of 7 participants' data from the analysis. Presumably this reflected the comparative difficulty of the wrist rotation response compared with simple keypresses, rather than carelessness by the participants. Errors and responses that were more than 2 *SDs* from the mean for that condition were excluded from the analysis. Mean reaction times for each object in each condition were computed for each participant. These were averaged over objects for the participants analysis and over participants for the materials analysis.

For the participants analysis, mean correct response times for each condition were subjected to a within-subjects ANOVA with the independent variables of object compatibility (clockwise or anticlockwise), response mapping (clockwise for upright objects and anticlockwise for inverted objects [C-UP] and anticlockwise for upright objects and clockwise for inverted objects [AC-UP]), and response (clockwise or anticlockwise). There were significant main effects of object compatibility and direction of response. Responses to objects compatible with a clockwise wrist rotation were faster ($M = 752.0$ ms) than responses to objects compatible with an anticlockwise rotation ($M = 834.4$ ms), $F(1, 26) = 115.83, p < .001$. Anticlockwise wrist rotation responses ($M = 768.5$ ms) were executed faster than clockwise wrist rotation responses ($M = 818.0$ ms), $F(1, 26) = 48.96, p < .001$. There was a significant two-way interaction between response mapping and object compatibil-

³In fact, and this is a point we take up in the *Discussion* section, using object inversion to cue wrist rotation responses results in an ambiguity in the affordances offered by the object. The central point is that for some objects (e.g., a bottle) their physical shape when inverted affords a clockwise wrist rotation merely to be grasped but an anticlockwise rotation if they are to be grasped in order to be returned to their normal position, because this maximizes the "end-state comfort" of the movement (see Rosenbaum et al., 1990).

ity, $F(1, 26) = 5.28, p < .05$ (see Figure 4), and a significant three-way interaction between object compatibility, direction of response, and response mapping, $F(1, 26) = 4.85, p < .05$. Pairwise comparisons (Newman-Keuls) of the interaction between response mapping and object compatibility showed that for objects compatible with a clockwise wrist rotation, the 38.1-ms reaction time advantage for the C-UP over the AC-UP mapping was significant, $q(2, 26) = 7.10, p < .01$, whereas for the objects compatible with an anticlockwise wrist rotation, the 13.4-ms reaction time advantage for the C-UP mapping was not, $q(2, 26) = 2.50, p > .05, MSE = 1,555$. The three-way interaction is most easily understood as an interaction between object inversion (defined by response direction and mapping) and object compatibility. For the class of objects compatible with a clockwise wrist rotation, responses were on average 24 ms slower when the object was inverted, whereas for the objects compatible with an anticlockwise wrist rotation the difference was only 4 ms.

To confirm that this provides the best account of the three-way interaction, we performed two separate analyses. In the first we analyzed the Response \times Object Compatibility interaction for each mapping to see whether the result could be attributable to the occurrence of a Simon effect of object compatibility on responses for one mapping but not the other. Within neither mapping was there a significant Response \times Object Compatibility interaction, although this interaction approached significance in the C-UP mapping. For the C-UP mapping, $F(1, 26) = 3.81, p = .062$, whereas for the AC-UP mapping, $F(1, 26) = 1.23, p = .278$. In contrast, when the data were broken down by object type, a significant interaction was found between mapping and response for the clockwise-compatible objects, $F(1, 26) = 5.14, p = .032$, but not for the anticlockwise-compatible objects ($F = 0.13, p = .717$). Finally, the predicted interaction between direction of response and object compatibility was not significant, $F(1, 26) = 0.46, p = .503$.

Error rates. The pattern of error rates was similar to that of response times except for the effect of mapping (see Figure 4). More errors were made with the C-UP mapping

than with the AC-UP mapping, $F(1, 26) = 11.79, p < .005$. This is the opposite of the pattern found in the response time data, where the C-UP mapping was faster than the AC-UP mapping, and it suggests that there could have been a trade-off between speed and accuracy across mappings. However, comparison of the graphs in Figure 4 indicates that no such trade-off was occurring between mapping and object compatibility. The only other significant effect was a main effect of object compatibility, with responses to clockwise-compatible objects ($M = 3.22$) producing fewer errors than responses to anticlockwise-compatible objects ($M = 8.0$), $F(1, 26) = 57.06, p < .001$.

Materials analysis. The response time data were analyzed with objects as a random factor (nested within object compatibility). The pattern of results was similar to the pattern with participants as a random factor. The main effect of object compatibility was significant. Objects compatible with a clockwise wrist rotation were responded to faster ($M = 752.0$ ms) than objects compatible with an anticlockwise wrist rotation ($M = 837.7$ ms), $F(1, 38) = 20.37, p < .001$. There was also a significant main effect of response mapping. Responses to the C-UP mapping ($M = 783.1$ ms) were faster than those to the AC-UP mapping ($M = 801.9$ ms), $F(1, 38) = 19.58, p < .001$. In addition, there were significant two-way interactions (a) between direction of response and mapping, $F(1, 38) = 6.08, p < .05$, which was not present in the participants analysis and corresponds to a main effect of object inversion, and (b) between object compatibility and mapping, $F(1, 38) = 7.31, p = .01$. The three-way interaction between object compatibility, response direction, and mapping was not significant. For the effect of most interest, the interaction between mapping and object compatibility, we carried out a calculation of $\text{Min } F'$, which gave a nonsignificant result: $\text{Min } F'(1, 57) = 3.06$, critical value at $\alpha (.05) = 4.03$.

Discussion

The main effect of object compatibility is readily explained by the fact that the objects compatible with clock-

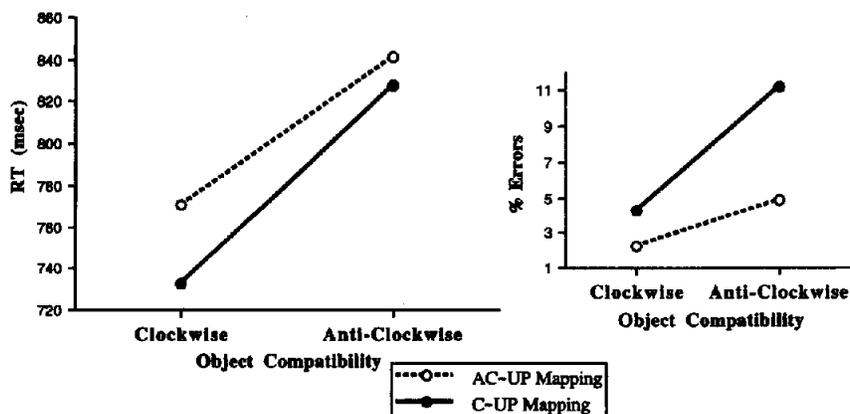


Figure 4. Mean reaction times (RTs) and error rates for Experiment 3 as a function of object compatibility (clockwise [C] or anticlockwise [AC]) and response mapping (UP = upright).

wise wrist rotations were, in most cases, larger than the objects compatible with anticlockwise wrist rotations. More important, perhaps, was that objects compatible with clockwise wrist rotations possessed more salient axes about which their inversion was defined, which made the judgment of object inversion, and hence which response to execute, easier.

The effect of response direction (anticlockwise wrist rotations were executed, on average, 41 ms faster than clockwise ones) likely reflects a preference for rotating the wrist in the anticlockwise direction. In addition, however, it can be seen to reflect the interpretation, discussed below, of an interaction between object inversion, response, and object compatibility (see Figure 5).

The most interesting results are the interaction between object compatibility and response mapping and the lack of the predicted two-way interaction between response direction and object compatibility. As in Experiments 1 and 2, the actual response made (clockwise or anticlockwise wrist rotation) was determined by two factors, mapping and object inversion. The lack of an interaction between the response made and object compatibility, implies, at first, that no facilitation or interference was produced by the grasp compatibility of the objects at the level of individual responses. There are several possible reasons for this. If response codes were automatically generated by the stimuli, and if these response codes included the parameter of wrist rotation, they may have had time to decay before the required response was retrieved (see, e.g., Hommel, 1994b). Reaction times in Experiment 3 were from 100 to 200 ms longer than in Experiments 1 and 2, and error rates were also considerably higher. Thus the translation from object inversion to a direction of wrist rotation seems to have been a more difficult assignment than translation from object inversion to a left-right push-button response.

Alternatively, wrist rotation may be a component of reaching that is not planned prior to movement initiation, even in goal-directed actions. Unlike grasp type, for which there is evidence of planning before movement onset (Klatzky et al., 1995), wrist rotation may unfold only as part of a synergy during an actual reaching movement. If this is the case, providing prior information about the direction of

wrist rotation—even explicitly as part of a precue—should result in little or no facilitation. A similar point was raised by Klatzky et al. (1989) with respect to partial information about hand shape.

The interaction between the object's grasp compatibility and mapping can be described as follows. The advantage for the C-UP over the AC-UP mapping was much greater (38 ms vs. 13 ms) for the clockwise-compatible objects than for the anticlockwise-compatible objects (see Figure 4). This result might be explainable by a salient features account (Weeks & Proctor, 1990) in which the most salient (upright) stimulus was paired with a clockwise rotation. Two problems are apparent with such an explanation. First, the effect occurred only for the clockwise-compatible objects. As was mentioned above, one of the reasons responses to the anticlockwise-compatible objects were longer was that objects in this group had less salient axes about which their inversion was defined. This lack of a salient upright-inverted dimension might, then, explain why the effect operated only for one class of objects. However, although deciding whether the anticlockwise-compatible objects were upright or inverted did take participants longer, this should have affected only their decision time and not the relative advantage of translating the results of that decision to a response. Second, such an account would have to assume that the clockwise wrist rotation represented the most salient response. The data do not support this, because clockwise wrist rotations were significantly slower than anticlockwise ones, and reaction time seems to be the only available criterion for evaluating relative salience.

A closer consideration of the stimuli allows us to suggest an interpretation based on the affordances of the objects in each of the two categories. It was originally presumed that both types of object afforded a grasp involving a clockwise or anticlockwise wrist rotation regardless of whether they were upright or inverted. The orientation of the opposition axis in the object remains the same whether it is upright or inverted. However, the way we grasp an object is influenced by the actions we can perform with it. In particular, the way the hand rotates to grasp an object is sensitive to the desired final position of the object in a way that grip size, for

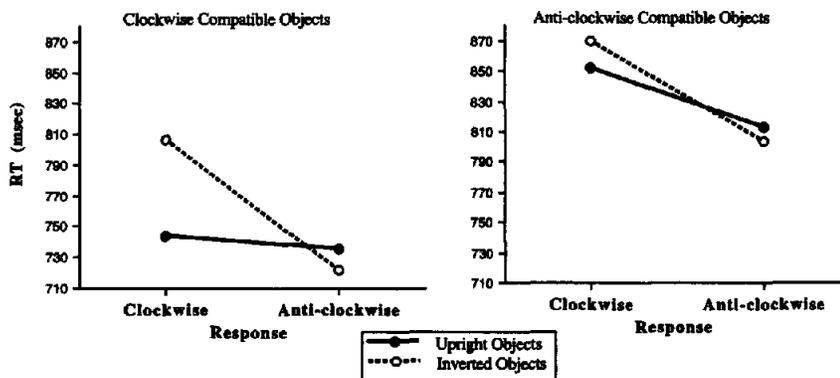


Figure 5. Mean reaction times (RTs) for Experiment 3 as a function of wrist rotation compatibility, response executed, and object inversion.

example, is not. One of the actions that an inverted object affords is a grasp that results in returning it to its upright position. In this case an inverted object of the clockwise-compatible type (such as an aerosol can) would require a grasp with an anticlockwise wrist rotation. Such a grasp maximizes the end-state comfort of the potential movement that would result in the object's being in a position for normal use (Rosenbaum et al., 1990). If this were the case, the C-UP mapping would maintain compatibility both when the object was upright and when it was inverted (because clockwise responses were required for upright objects and anticlockwise responses for inverted objects under this mapping rule). In contrast, with the anticlockwise-compatible objects no such effect of mapping would be expected. This is because these objects still require the same grasp type, and direction of wrist rotation, regardless of whether or not they must be returned to upright (e.g., a stapler lying on its back and positioned at right angles to the line of sight). In all cases they must be grasped from above, with the thumb and fingers (of the right hand) turning anticlockwise to align themselves along the opposition axis. If the object is to be returned to upright, this must be achieved by subsequent manipulations after the initial grasp has been performed. This account would predict, therefore, that anticlockwise responses should always be faster to the anticlockwise-compatible objects, regardless of inversion, whereas clockwise responses should be faster only to upright objects in the clockwise-compatible category.

An examination of the data broken down by the responses executed to each object type and at each inversion gives some support to this explanation of the significant two-way interaction (see Figure 5). For the clockwise-compatible objects, clockwise wrist rotations were executed faster to upright objects than to inverted ones, whereas anticlockwise rotations were executed faster to inverted objects than to upright objects. In contrast, for the anticlockwise-compatible objects, the difference between responses to upright and inverted objects was minimal. On average, anticlockwise rotations were executed faster than clockwise rotations regardless of inversion, with only a very slight advantage for clockwise rotations to upright objects and anticlockwise rotations to inverted objects.

Because of the potential importance of object inversion on the affordances generated by the objects, we carried out a further analysis using inversion as a factor. It is important to point out that in this and any other SRC study in which a stimulus property is used to cue a response under a mapping rule, one of the three factors of mapping rule, response-relevant stimulus property, and response is always redundant because it can be derived from the other two. An analysis using object inversion and response as factors together with object compatibility is exactly equivalent to an analysis using mapping and response. Thus the interaction between object compatibility and mapping corresponds to a three-way interaction between object inversion, response, and object compatibility. Separate analyses of this interaction broken down by object compatibility help to clarify the data presented in Figure 5. For the clockwise-compatible objects the interaction between response and inversion was signifi-

cant, $F(1, 26) = 4.94, p = .034$, whereas for the anticlockwise-compatible objects it was not, $F(1, 26) = 0.66, p = .423$, a result that lends support to the interpretation given above of the differential effect of object inversion on the affordances of the two types of objects.

This analysis, therefore, suggests caution in interpreting the insignificant Response \times Object Compatibility effect as evidence against the existence of a Simon effect from the objects' affordances. However, a full understanding of the effect would have to involve further experimentation in which the effects of mapping and object inversion were not confounded. The data nonetheless provide preliminary evidence for the existence of compatibility relations between an object's affordance for grasping and responses that share a component of that action other than hand choice.

General Discussion

The most striking and theoretically significant finding in these experiments is the fact that compatibility effects, of a stimulus property irrelevant to response determination, were obtained with a wide variety of natural stimuli. The first two experiments showed that the irrelevant orientation of a centrally placed object produced a compatibility effect on left-right responses executed by the left and right hands but not on left-right responses executed by adjacent fingers of the same hand. Only when there was a relation between the different responses and the different affordances produced by varying the objects' orientations did a compatibility effect emerge. The fact that this compatibility relation occurred with a property such as object orientation is important. Left-right orientation was extracted across the stimulus set, even though the perceptual input specifying orientation varied widely for each individual object and, moreover, was not even relevant to the task.

In typical SRC experiments involving spatial compatibility, left-right codes are formed on the basis of a few fixed features of the task display. A colored spot might appear at one or two locations, for example. From trial to trial the feature specifying "leftness" or "rightness" remains identical, facilitating a representation of the display that includes left or right codes. In contrast, object orientation is not a fixed visual feature of the display. The pattern of stimulation that signals a left or right orientation is very different for each individual object. For some objects, such as a knife, the principal axis is the same axis along which the object's orientation is defined. For others, such as a jug, orientation is defined along an axis orthogonal to the principal axis. This no doubt contributes to the lack of any evidence, from Experiment 2, for the existence of dimensional overlap between left-right orientation and the left-right responses. The fact that a compatibility effect was found in Experiment 1, in which the left and right hands executed the responses, cannot therefore be attributed to a Simon effect based on the abstract coding of stimulus orientation. Such an explanation is not consistent with the disappearance of the effect in the unimanual condition. Instead, the results of Experiment 2 imply that it was not the left-right coding of orientation itself that produced the compatibility effect in Experiment 1,

but rather the affordances for action that object orientation affects, which in this experiment, we proposed to be the relative ease with which the objects could be grasped by the left or right hand.

The left-right coding proposed to account for the compatibility effect in the first experiment is based on the organization of the visuomotor system. Orientation is an object property that must be represented accurately to guide actions, in contrast to the requirements of object recognition, where the effects of different viewpoints need to be filtered out. The production of left-right codes from object orientation suggests that at some level this distinction is important to actions. The results from Experiments 1 and 2 imply that this distinction corresponds to the left-right effector systems geared to interact with visual objects, rather than to a left-right property inherent in orientation itself. The left-right organization of the human body presumably is the ultimate source even of our ability to form relative left-right spatial codes. This does not, of course, imply that all cases of spatial compatibility result from the activation of responses congruent with the physical location of the stimulus. It does imply, however, that the physical organization of the body is important in enabling left-right coding at any level, even when the task environment does not afford specific actions. In representing objects that do afford specific actions, that coding must include absolute relations between the effector systems and the properties of the objects to which they are sensitive. Most affordances are specified by complex visual information taken in conjunction with the physical state of the perceiver. Such visual information may not always lend itself to the formation of simple stimulus codes that are then able to overlap with a response dimension. Instead, relatively simple response codes may be formed as a result of the affordances that the complex visual information specifies.

Accounts of SRC that involve the actions visual objects potentiate do not replace other more abstract coding accounts. It is, of course, well established that compatibility effects occur for spatial components of the stimuli when the responses do not involve affordances for action. For instance, they occur for verbal left-right responses (Weeks & Proctor, 1990). Thus the existence of abstract cognitive coding is not in question. What is in question is that this is the only type of coding that response compatibility arrangements can produce. We propose that there is a continuum of response codes capable of being generated, ranging from the most abstract, relative level down to those more directly related to the actions made possible by the visual environment. Such a view is consistent with the neurophysiology of the visuomotor system, where there is evidence for a continuum of codes at many levels of abstraction, including those insensitive to the way the responses are executed (see, e.g., Alexander & Crutcher, 1990a).

Even within abstract SRC arrangements the motor system has a central role in the production of directional codes. Within such domains the notion of dimensional overlap provides a good model for predicting the conditions under which compatibility effects of both relevant and irrelevant stimulus dimensions will obtain. In the case of the Simon effect this model holds that the compatibility effect arises

from the automatic activation of a response congruent with an automatically generated spatial response code (Kornblum et al., 1990). It does not, however, provide an explanation of why such codes are automatically generated. Theories that aim to explain the basis of these codes have in fact involved the motor system. In particular, Nicoletti and Umiltà (1989, 1994; see also Stoffer & Yakin, 1994) put forward an account based on the premotor theory of attention (see Rizzolatti, Riggio, Dascola, & Umiltà, 1987) to explain the generation of the directional spatial codes underlying the Simon effect. Their model asserts that a directional left-right code is formed with reference to the current position of attention. The basis for the code is the directional component of the premotor saccade command that is present whenever covert attention shifts. It does not depend on a saccade's actually being executed, because the premotor model assumes that both overt and covert attentional shifts depend on essentially the same motor program. Simon effects of stimulus location will occur whenever the imperative stimulus appears to the right or left of the current position of attentional focus under conditions in which attentional shifts are made possible.

Attentional processes and the codes they generate are, no doubt, important in a wide range of SRC arrangements, from the most abstract to those involving more meaningful stimuli and responses. In abstract SRC arrangements, the directing of attention is perhaps the only affordance that the stimuli have. Where they are more meaningful, however, codes generated by other actions afforded by the stimuli may be generated by processes not dissimilar to the premotor mechanisms involved in the planning of potential saccades. Indeed, the empirical question we set out to investigate was the extent to which affordances other than those directly involved in the visual processing of the stimulus (such as shifts of attention) were also activated despite being irrelevant to the task.

Because of the range of codes capable of being generated by visual stimuli it may often be extremely difficult to separate the precise causes of compatibility effects. If the chosen stimuli have a natural significance for action, and the responses also share a component of that action, then we would argue that compatibility effects would arise in part from the potentiation of the afforded action. This does not preclude the possibility of other codes' being generated by the same stimulus property. The location of a graspable object, for instance, will influence the motor patterns that are required for a successful reach-and-grasp movement. Any codes based on those motor patterns will no doubt share a directional component present in other codes. Disentangling the relative contributions of such codes on compatibility effects presents a serious problem. When, however, a stimulus property that selectively affects the affordances for action along a simple response dimension, such as the left or right hand, is at the same time not easily coded into a simple stimulus code, the cause of any compatibility effects is much clearer. The results of Experiments 1 and 2 follow this pattern. Object orientation, at least when presented across a series of natural objects, does not seem to produce a simple left-right stimulus code capable of overlapping with a

left-right response dimension. It does, however, facilitate or interfere with responses produced by the left and right hands, which implies that what matters is the relation between object orientation and the hands rather than simply the left-right status of the response keys.

The involvement of the action system does not preclude higher level compatibility effects. It does, however, provide a basis for their existence in cases where the properties of the visual stimuli that produce them can otherwise be categorized only in an arbitrary manner. Action-related codes thus extend, rather than replace, other coding accounts of SRC effects to situations where the varying dimensions have a natural significance for action and are not fixed perceptual properties of the display.

Many of the points mentioned above concerning the importance of the action system in compatibility effects have been raised by Michaels (1988, 1993). In particular, Michaels (1993) doubted the generalizability of the coding approach to situations where the relation between the visual stimuli and the action system of the perceiver was meaningful—unless, that is, the notion of response codes also included information about the details of how the actions were to be executed (Michaels, 1993, p. 1125). Similarly, Michaels (1993) criticized the Kornblum et al. (1990) idea of dimensional overlap for failing to provide any basis in the perception-action system for the dimensions involved. Although the primary purpose of the experiments we carried out was to use the SRC paradigm as a tool for investigating action potentiation, rather than to redefine SRC itself, the action account we propose answers some of these criticisms. Insofar as coding is involved, it arises from the potentiation of specific actions afforded by the object, in this case reaching by a particular hand, and consequently, the stimulus dimensions along which compatibility effects emerge are based on their relevance for controlling those actions. The results of Experiment 3 also suggest that the way we habitually use objects may influence even the low-level affordances they generate. Although interpreting the results of Experiment 3 proved a more complex task than was the case for Experiments 1 and 2, an action account does provide a coherent explanation not readily forthcoming from more abstract coding accounts.

In conclusion, the present study provides evidence consistent with the view that the actions afforded by a visual object are intrinsic to its representation. According to this position, representing visual information involves representing information about possible actions and thereby potentiating them. One consequence of this is that intended actions are formed from, and informed by, already existing visuomotor representations. Actual actions are produced by the selection and elaboration of such representations. Neuropsychological and physiological evidence confirms the importance of action in visual processing and the highly integrated nature of visual and motor representations, facts that make the automatic activation of action components by visual stimuli feasible. A further consequence is that any explanation of the compatibility between complex natural visual stimuli and motor responses needs to be informed by the actions made possible by those stimuli. The cognitive approach to SRC is perfectly

consistent with the view that codes based on the actions an object affords play a part in determining the compatibilities that emerge in realistic stimulus-response environments. Taking account of such relations is necessary if the approach is seriously to extend to such domains.

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Appendix A

Objects Used in Experiments 1 and 2

Note. In Experiment 2, Objects 2 and 5 were not present.

- | | |
|----------------------|----------------------------|
| 1. Iron | 12. Teapot |
| 2. Kettle | 13. Coffee pot |
| 3. Large jug | 14. Watering can |
| 4. Saw | 15. Glass saucepan |
| 5. Saw | 16. Electric carving knife |
| 6. Sieve | 17. Frying pan |
| 7. Dustpan and brush | 18. Handled dustpan |
| 8. Frying pan | 19. Metal saucepan |
| 9. Medium jug | 20. Glass coffee pot |
| 10. Plant waterer | 21. Decorative jug |
| 11. Kettle | 22. Iron |

Appendix B

Calculation of Min F'

If F_1 = the F ratio for the effect by participants with n and n_1 degrees of freedom and F_2 = the F ratio for the effect by objects with n and n_2 degrees of freedom, then $\text{Min } F'(n, j) = (F_1 \cdot F_2) / (F_1 t + F_2)$, and the degrees of freedom, j , = the nearest integer to $(F_1 + F_2)^2 / (F_1^2/n_2 + F_2^2/n_1)$.

Appendix C

Objects Used in Experiment 3

Objects compatible with a clockwise wrist rotation from start position:

- | | |
|----------------------|------------------------|
| 1. Aerosol can | 11. Lamp stand |
| 2. Jug kettle | 12. Tall glue bottle |
| 3. Wine bottle | 13. Teapot |
| 4. Glass coffee pot | 14. Plastic jug |
| 5. Jug | 15. Washing up bottle |
| 6. Large jug | 16. Candlestick holder |
| 7. Tall milk carton | 17. Squash bottle |
| 8. Aerosol | 18. Brown bottle |
| 9. Plant sprayer | 19. Milk jug |
| 10. China coffee pot | 20. Watering can |

Objects compatible with an anticlockwise wrist rotation from start position:

- | | |
|----------------------|-------------------|
| 1. Radio | 11. Iron |
| 2. Floor brush | 12. Hairbrush |
| 3. Dustpan and brush | 13. Large stapler |
| 4. Knife | 14. Small stapler |
| 5. Iron | 15. Wire brush |
| 6. Nailbrush | 16. Nailbrush |
| 7. Teaspoon | 17. Sieve |
| 8. Wooden spoon | 18. Tea strainer |
| 9. Saucepan | 19. Small jar lid |
| 10. Small jar | 20. Small padlock |

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