Action for Perception: A Motor–Visual Attentional Effect

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Five experiments investigated whether preparation of a grasping movement affects detection
and discrimination of visual stimuli. Normal human participants were required to prepare to
grasp a bar and then to grasp it as fast as possible on presentation of a visual stimulus. On the
basis of the degree of sharing of their intrinsic properties with those of the to-be-grasped bar,
visual stimuli were categorized as "congruent" or "incongruent." Results showed that
grasping reaction times to congruent visual stimuli were faster than reaction times to
incongruent ones. These data indicate that preparation to act on an object produces faster
processing of stimuli congruent with that object. The same facilitation was present also when,
after the preparation of hand grasping, participants were suddenly instructed to inhibit the
prepared grasping movement and to respond with a different motor effector. The authors
suggest that these findings could represent an extension of the premotor theory of attention,
from orienting of attention to spatial locations to orienting of attention to graspable objects.

Selective attention is the name given to the capability of selecting a particular stimulus according to its physical properties, way of presentation, or previous contingencies and instructions. After selection, the stimulus is processed and, if convenient for the individual, acted on.

The mechanisms at the basis of selective attention are still a matter of debate. The traditional view is that selective attention is controlled by a supramodal system "anatomically separate from the data processing systems" (Posner & Petersen, 1990, p. 26). Like the sensory and motor systems, this "attention system" performs operations on specific inputs. It interacts with other centers of the brain but maintains its own identity (Posner & Petersen, 1990). On the basis of data obtained from brain imaging experiments (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Posner, Petersen, Fox, & Reichle, 1988), it has been suggested that the attention system is not unitary but consists of at least two independent systems: a posterior one subserving spatial attention and an anterior one devoted to attention recruitment and control of brain areas involved in complex cognitive tasks (Posner & Dehaene, 1994).

Another view of selective attention is that it derives from mechanisms that are intrinsic to the circuits underlying perception and action. Attention is modular, and there is no

need to postulate control mechanisms anatomically separate from the sensorimotor circuits. This account of selective attention was originally formulated for spatial attention (premotor theory of attention; Rizzolatti & Camarda, 1987; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; see also later discussion). A version of it was recently proposed as well for selection of visual stimuli among distractors (Chelazzi, Miller, Duncan, & Desimone, 1993; Duncan, 1996).

The "premotor" account of spatial attention mechanisms is deeply rooted in neurophysiological findings on how space is coded and transformed into action in the nervous system. In primates, space is coded in a series of parieto-frontal circuits working in parallel (Colby & Duhamel, 1996; Gross & Graziano, 1995; Rizzolatti, Fadiga, Fogassi, & Gallese, 1997; Rizzolatti, Riggio, & Sheliga, 1994). There are three functional aspects of these circuits that are worth noting. First, none of them contain anything that resembles a spatial multipurpose map. Second, in each of them spatial information is elaborated for specific motor purposes. Third, space is not coded identically in various cortical areas. The coordinate frame in which space is coded depends on the motor requirements of the effectors that a given circuit controls (see Rizzolatti et al., 1994).

Given this strict link between space coding and action programming, the premotor theory of attention postulates that spatial attention is a consequence of an activation of those cortical circuits and subcortical centers that are involved in the transformation of spatial information into action. Its main assumption is that the motor programs for acting in space, once prepared, are not immediately executed. The condition in which action is ready but its execution is delayed corresponds to what is introspectively called spatial attention. In this condition, two events occur: (a) There is an increase in motor readiness to act in the direction of the space region toward which a motor program was prepared, and (b) the processing of stimuli coming from that same space sector is facilitated. There is no need,

therefore, to postulate an independent control system. Attention derives from the mechanisms that generate action (see Rizzolatti & Craighero, 1998).

Although, in principle, all circuits responsible for spatially directed action can influence spatial attention (Chieffi, Gentilucci, Allport, Sasso, & Rizzolatti, 1993; Rizzolatti & Berti, 1990; Rizzolatti, Gentilucci, & Matelli, 1985; Tipper, Lortie, & Baylis, 1992), there is no doubt that in humans the central role in spatial attention is played by the circuits that code space for programming eye movements. Experiments in which the relations between attention and eye movements were either indirectly (Fischer, 1997; Hietanen & Rama, 1995; Rizzolatti et al., 1987; Shepherd, Findlay, & Hockey, 1986; Umiltà, Mucignat, Riggio, Barbieri, & Rizzolatti, 1994; Umiltà, Riggio, Dascola, & Rizzolatti, 1991) or directly (Kustov & Robinson, 1996; Sheliga, Craighero, Riggio, & Rizzolatti, 1997; Sheliga, Riggio, Craighero, & Rizzolatti, 1995; Sheliga, Riggio, & Rizzolatti, 1994) tested showed that the two mechanisms interact: Any time attention is directed to a target, an oculomotor program toward that target is prepared. Particularly significant in this respect are experiments in which the relations between attention and eye movements were directly tested (Sheliga et al., 1997; Sheliga, Riggio, Craighero, et al., 1995; Sheligo, Riggio, & Rizzolatti, 1995; Sheliga et al., 1994). Sheliga and coworkers instructed normal participants to pay attention to a given spatial location and to perform a predetermined vertical or horizontal ocular saccade at the presentation of the imperative stimulus. Results showed that the trajectory of ocular saccades in response to visual or acoustic imperative stimuli deviates according to the location of attention. The deviation increased as the attentional task became more difficult. Note that if spatial attention were independent of oculomotor programming, ocular saccades should not be influenced by location of attention.

A close link between spatial attention and eye movements was found as well by Kustov and Robinson (1996), who showed that, in macaque monkeys, the trajectories of saccades evoked by electrical stimulation of the superior colliculus changed depending on where attention was located. Particularly important was the finding that collicular excitability changed not only when the monkey was instructed to respond to the imperative stimulus by performing a saccade but also when it had to respond manually, keeping the eyes still on the fixation point. This latter finding demonstrates that a shift of attention without any preceding or subsequent eye movement determines a change in excitability of the oculomotor system. This is exactly what the premotor theory of attention would have predicted.

The close link between attention and eye movement preparation shown by the experiments just reviewed is, at first glance, in contrast with the data of some other experiments in which the relations between attention and eye movements were tested in a different manner. These experiments showed that, in certain conditions, individuals who were instructed to perform an eye movement toward a predetermined direction did not show facilitation in processing stimuli spatially congruent with the prepared eye movement (Klein, 1980; Klein & Pontefract, 1994; Stelmach,

Campsall, & Herdman, 1997, Experiment 6). In addition, although typically eye movements cannot be performed without a preceding attention movement (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd et al., 1986), the claim that such a dissociation may occur has been advanced recently (Làdavas, Zeloni, Zaccara, & Gangemi, 1997; Stelmach et al., 1997, Experiment 1). Is the interpretation of these results unequivocal? And, most important, are they sufficient to falsify the premotor theory of attention?

The most influential experiment showing that preparing an eye movement toward a target does not necessarily determine an attention facilitation to respond to that target was performed by Klein (1980, Experiment 1). Participants were instructed to make a predetermined saccadic eye movement from a central fixation point to one of two peripheral target dots when an asterisk appeared at either of the target positions. On occasional trials, a different stimulus—one of the peripheral targets briefly brightening—occurred. In response to brightening of either target, participants had to make a simple manual response. Results showed that eye movement latencies revealed a consistent compatibility effect. Manual latencies, however, were unaffected by the relations between location of the luminance increment and direction of the prepared eye movement. These results were interpreted as evidence that eye movement preparation does not produce attentional facilitation.

Another interpretation, however, is possible. In Klein's (1980) experiment, the task required participants to detect and discriminate the stimuli before making the saccade. Therefore, it is very likely that participants simply paid attention to the stimulus and only later, on directed attention, to the saccade target. According to the premotor theory of attention, attention allocation requires preparation of an eye movement. Thus, if participants had complied with instructions, they would have had to perform two interfering tasks simultaneously. It is likely that they performed only one of them. Thus, Klein's results do not falsify the premotor theory of attention, as claimed; in contrast, they are consistent with its predictions.

More recently, a claim basically similar to that of Klein (1980) was made by Stelmach et al. (1997, Experiment 6). In their experiment, participants were presented with a display consisting of a fixation cross and two boxes located on either side of the fixation cross. They had to respond manually to a visual target located inside one of the boxes and to make a saccade to the left or right, depending on verbal instructions. The time interval between the verbal cue and the visual target was manipulated. At some intervals, the target was presented before the cue (negative asynchronies). At other intervals, the order was reversed (positive asynchronies). In agreement with Shepherd et al. (1986), Stelmach et al. found that manual responses were faster when the target appeared in the position toward which the eye movement was prepared. However, they found that this effect was present also when the target was presented before the cue. They concluded that a coupling between eye and hand responses, rather than an attentional factor, was responsible for the Shepherd et al. (1986) results, as well as their own findings

when the cue preceded the target. However, they did not account for the fact that presentation of the visual target must have attracted attention even when the target was presented before the cue. Thus, regardless of the delay of the hand responses, the condition "same" (i.e., when target and cue coincided) was favored with respect to the condition "opposite" (i.e., when the cue followed the target). The same was true of ocular responses: The negative asynchrony condition was nothing but a regular attention-orienting experiment with an exogenous visual cue and a verbal imperative stimulus.

The second set of arguments raised against the premotor theory of attention claims that, if the premotor theory of attention is correct, any time there is an eye movement, there must be also a shift of attention in the same direction as the impending eye movement. One has to distinguish here between results from normal participants and results from patients. The possibility of dissociating eye movements and attention was recently investigated by Stelmach et al. (1997, Experiment 1), who studied whether the temporal order judgment of two simultaneously presented visual stimuli was affected by saccade execution and attentional allocation. The results showed that endogenous movements of attention were slower than actual eye movements. In regard to the premotor theory of attention, this finding is neutral. If one examines carefully the conditions in which the participant is required to move the eyes toward a certain target and the conditions in which attention but not the eyes should be moved, it becomes clear that in the former case the participant prepares a program and executes it, whereas in the latter case the participant prepares a program and simultaneously has to inhibit it. Thus, in this latter condition there are two motor programs that are simultaneously prepared. The findings of Shepherd et al. (1986) are in favor of this interpretation. In their experiment, attention was rapidly allocated to the peripheral location, because it was not interfered with by additional instructions but had simply to move to the peripheral stimulus, together with the eyes. Normally, attention moves fast and precedes eye movements.

In patient studies, confusion derives from lack of distinction between eye movements made with the purpose of positioning the fovea on a particular spatial location to extract information from it and eye movements that are executed without such a goal. An example of the latter comes from saccades executed on command without a precise target or from exploratory eye movements that are meant not to extract information from a particular location in space but, rather, to provide the individual with a global sampling of the environment. This distinction between target-directed movements on the one side and "meaningless" and exploratory movements on the other is supported by neurophysiological data. Single neuron experiments have shown that neurons in some cortical areas, such as the frontal eye fields, become active during target-directed eye movements but not during spontaneous saccades made in the dark or saccades made in light but without a task requirement or without an overt visual target (C. J. Bruce & Goldberg, 1985; Burman & Segraves, 1994; Goldberg &

Bruce, 1985; Goldberg & Bushnell, 1981). From these considerations, it appears clear that the mere execution of an eye movement is not necessarily accompanied by a spatial motor program and that a movement of selective attention occurs only for goal-directed eye movements. Because the premotor theory of attention claims that spatial attention is a consequence of preparation of a motor program for directing the eyes to a specific location, the absence of attentional effects for eye movements having other purposes is irrelevant to testing its validity. Similarly irrelevant for the premotor theory of attention are data showing that, in the case of a cortical lesion, eye movements may occur without a concomitant attentional shift (Làdavas et al., 1997). There is no reason whatsoever why disinhibition by peripheral stimulation of the center controlling eye movements should be accompanied by an attentional shift. Central programming of an eye movement produces spatial attention. The mere execution of an eye movement does not.

Whereas in primates eye movements are certainly the most important mechanism for selecting stimuli, there are also circumstances (e.g., stimuli presented very close to the face) in which eye movements are not crucial in selecting stimuli in space. In these circumstances, spatial attention should depend on circuits other than those related to eye movements. Probably the best documented evidence in favor of spatial attention not related to eye movements is that deriving from experiments conducted by Tipper et al. (1992). They studied, in normal participants, the effect of an irrelevant stimulus located in or out of the arm trajectory necessary to execute a pointing response. The results showed that an interference effect was present only when the distractor was located in the trajectory of the arm. Control experiments suggested that the effect was not due to a purely visual representation of the stimuli or to spatial attention related to eye movements. Rather, the organization of the arm–hand movement determined a change in the attentional relevance of stimuli close to the hand or far from it.

The aim of the present study was to investigate whether the premotor theory can be extended to attention related to objects. Objects are represented in both the ventral stream and the dorsal stream. However, the processes carried out in the two streams are different. Whereas processing in the ventral stream is responsible for perceptual and cognitive representations of the visual characteristics of objects and their significance, processing in the dorsal stream underlies the organization of the appropriate object-related hand movements (Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1995). There is increasing neurophysiological evidence (Rizzolatti et al., 1988; Sakata & Kusunoki, 1992) that this "pragmatic" function is performed by a circuit in the dorsal stream that codes the intrinsic visual characteristics of the objects and transforms them into the appropriate distal movements (for a review, see Jeannerod, Arbib, Rizzolatti, & Sakata, 1995).

Evidence in favor of the presence in humans as well of a strict link between the representation of an object's visual properties and specific motor programs to act on it has been

provided by experiments showing a "visuomotor priming effect" (Craighero, Fadiga, Umiltà, & Rizzolatti, 1996; see also Craighero, Fadiga, Rizzolatti, & Umiltà, 1998). In these experiments, visual presentation of a task-irrelevant drawing of a graspable object decreased the time to initiate a grasping movement to a real object the intrinsic properties of which were congruent with those of the visual object. This clearly indicates that a specific grasping movement is automatically activated by the sight of a graspable object and that activation increases motor readiness to execute the congruent movement. A recent positron emission tomography experiment confirmed this finding by showing activation of the premotor cortex by the mere observation of tools of common use (Grafton, Fadiga, Arbib, & Rizzolatti, 1997).

The rationale of the experiments reported here was as follows. We assumed that allocation of attention to a graspable object is a consequence of preparing a grasping movement to that same object. Thus, we predicted that, when a specific grasping movement was activated, there would be both an increase in the motor readiness to execute that movement and a facilitation in visual processing of graspable objects the intrinsic properties of which are congruent with the prepared grasping.

The results reported later supported the hypothesis. The detection of a visual object was facilitated by the preparation of a grasping movement congruent with the object's intrinsic properties. This finding strongly suggests that the premotor theory of attention is not limited to orienting attention to a spatial location but can be generalized to the orienting of attention to any object that can be acted on.

Experiment 1

Experiment 1 was designed to verify the presence of facilitation in the detection of a visual stimulus similar in orientation and shape to a real object that the participant was ready to grasp. Participants were instructed to prepare a grasping movement to one of two bars that differed in orientation (Figure 1B). They had to execute the prepared grasping movement on presentation of a bar on the computer screen (Figure 1A and Figure 2A). The orientation of the visual bar could match (congruent condition) or not match (incongruent condition) the orientation of the to-be-grasped bar. By comparing the grasping movement latencies for the congruent condition and the incongruent condition, we were able to assess whether the congruence between visual and physical objects affected the speed with which the grasping response was executed.

Method

Participants. Fourteen students at the University of Parma between the ages of 20 and 25 years served as participants. All were right-handed, had normal or corrected-to-normal visual acuity, and were naive as to the purposes of the experiment.

Apparatus, stimuli, and procedure. The experiment took place in a sound-attenuated room dimly illuminated by a halogen lamp. A microcomputer (INTEL 486) was used for stimulus generation and response recording. Participants were seated in front of the

computer screen with their head positioned on a chin rest. The distance between the computer screen and participants' orbital plane was 57 cm.

The go signal consisted of one of three pictures (white lines on a black background) displayed around the fixation cross (cross arm, 1°): a rectangle (6° × 2°) rotated 45° clockwise, a rectangle (6° × 2°) rotated 45° counterclockwise, or a circle (diameter: 3°; Figure 1A). The response consisted of grasping, as fast as possible, a red plastic bar (6 × 2.5 cm) inserted inside a rectangular hole hollowed in a white plastic disk (diameter: 12 cm) and glued to it (Figure 1B). The hole was larger than the bar and allowed the participants to insert the thumb and index finger in it to grasp the bar. On 50% of trials, the bar orientation was −45° (i.e., counterclockwise) with respect to the sagittal plane of the participant's body; the orientation was 45° (i.e., clockwise) on the remaining trials.

The experimental procedure is schematically shown in Figure 1A. Before the experiment, participants were trained to grasp the bar, which was oriented clockwise or counterclockwise, without looking at it. Bar orientation was randomly changed trial by trial, and the participants were informed, at the beginning of each trial, about the orientation of the bar by the word *left* (counterclockwise) or *right* (clockwise) on the computer screen. When ready, they initiated the trial by pressing a switch with their right hand shaped in a pinch position. They had to maintain the switch press until the response onset. The switch was placed on the right side on a horizontal plane. The beginning of the trial was signaled by the fixation cross, which appeared at the center of the computer screen. After a variable interval (250–750 ms), the go signal was presented. Each of the three pictures was presented randomly on an equal number of trials, and participants were explicitly instructed to execute the response while disregarding the different shapes or orientations of the go signal. They responded by grasping and lifting the bar with their right hand. The bar was located in front of the switch (distance: 12 cm), out of the participant's sight.

There were three experimental conditions. In the congruent condition, the go signal was a bar the orientation of which matched the orientation of the bar to be grasped. In the incongruent condition, the go signal was a bar the orientation of which did not match the orientation of the bar to be grasped. Finally, in the neutral condition, the go signal was the circle, which did not provide orientation information and was not included in the set of to-be-grasped objects. For each bar orientation, the number of trials for congruent, incongruent, and neutral conditions was identical. Thus, the shape of the go signal gave no helpful information about the to-be-grasped bar orientation. Reaction time (RT) was the time between the go signal and the releasing of the home position.

Four types of error arose from inappropriate responding, and all were controlled on-line by the computer, except the one concerning accuracy of the grasping movement. They were *anticipations* and *retardations* in the initiation of the grasping movement, *retardations in execution* of the grasping movement, and *wrong movements*. Anticipation errors were RTs shorter than 120 ms. Retardation errors were RTs longer than 1,000 ms. Retardation in execution errors occurred when the movement time (i.e., the time between the releasing of the home position and the lifting of the object) was longer than 2,000 ms. Wrong movement errors referred to trials in which participants executed the wrong grasping movement (e.g., participants performed the grasping movement to the clockwise bar when the orientation of the bar was instead counterclockwise). Movement accuracy was recorded visually by an experimenter located behind the participants. All trials with errors, regardless of their type, were repeated. Each participant was tested in one
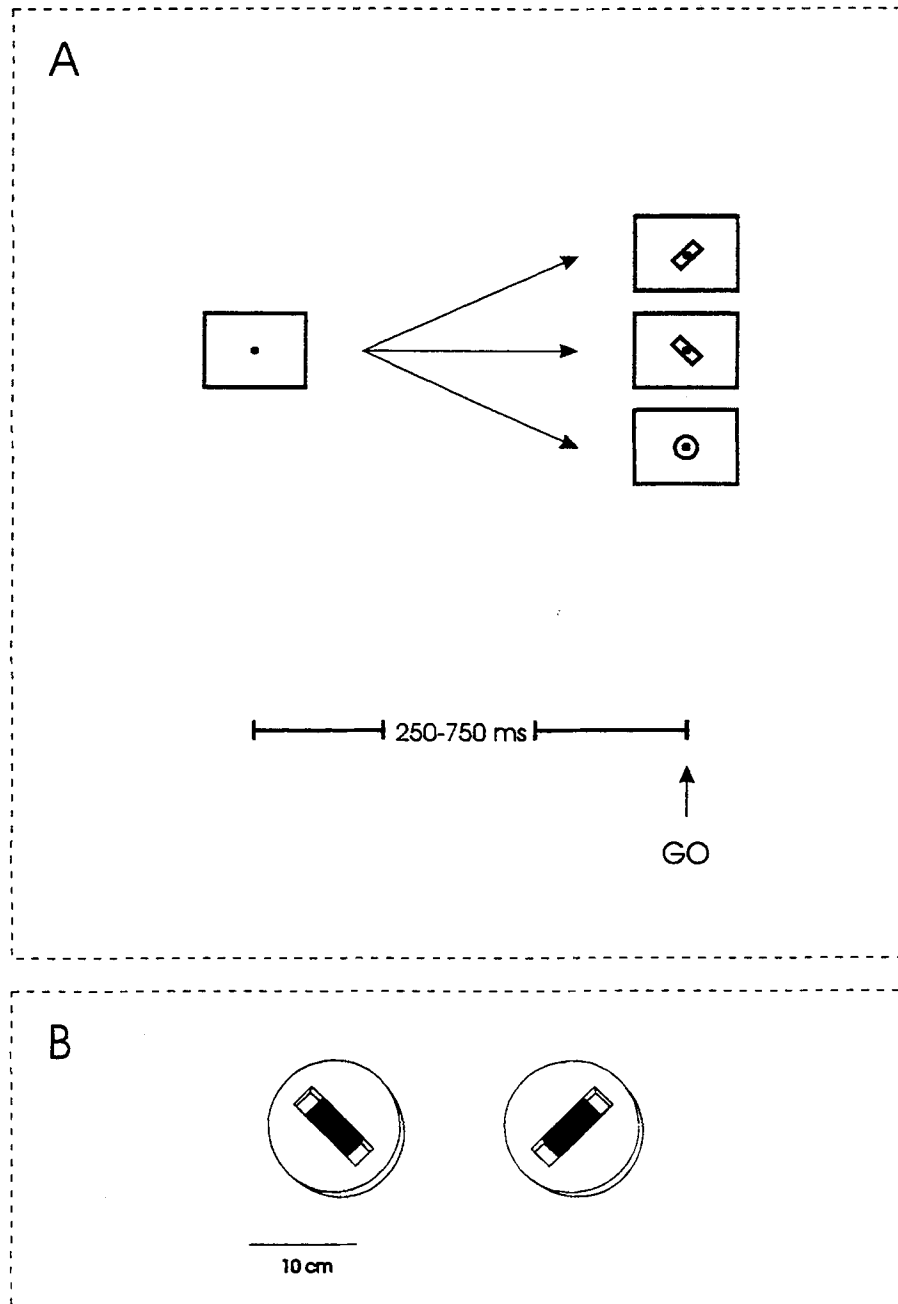
Figure 1. A: Schematic representation of the procedure for Experiment 1. Experimental events are represented as computer displays. B: Objects that the participants were instructed to grasp. These objects were used in all experiments.

experimental session that comprised 120 randomized trials and was preceded by about 30 practice trials.

Results and Discussion

RT analysis. The mean RTs for each condition are shown in Table 1. An analysis of variance (ANOVA) was performed on mean RTs transformed via the Vincentization procedure introduced by Ratcliff (1979; see also De Jong, Liang, & Lauber, 1994). Mean RTs were calculated for the first to the fifth bin of the rank-ordered raw data, separately for each bar orientation and for each experimental condition. More precisely, we calculated, for each participant, the RT distributions for congruent, incongruent, and neutral conditions, separately for each bar orientation. Then we divided each of these distributions into five proportional bins, such
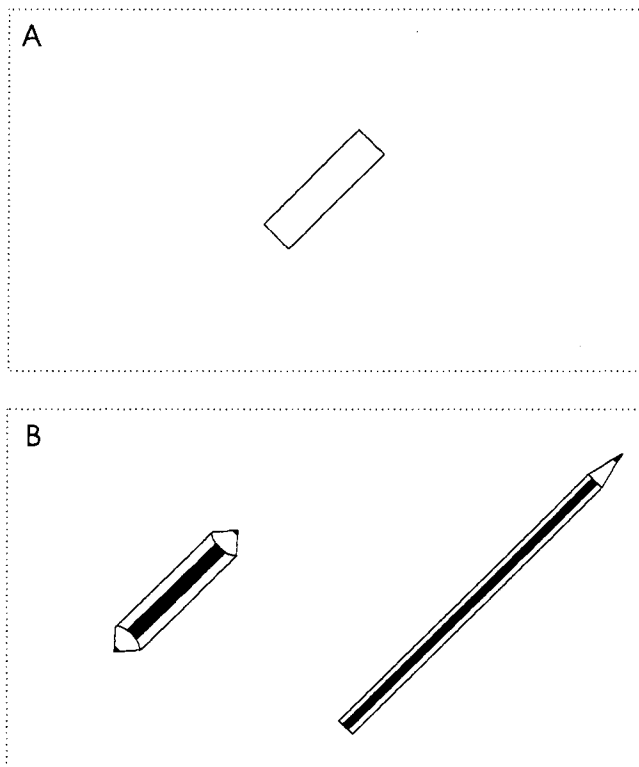
Figure 2. A: Visual stimulus presented in Experiment 1. B: Visual stimuli presented in Experiment 2. Only the clockwise-oriented stimuli are shown.

that each bin contained the same proportion (one fifth) of trials, and calculated the mean value of each bin. The difference, at each bin, between the means of the experimental conditions is a bin-by-bin measure of the studied effect that, when plotted as a function of the average RT, provides a measure of the changes over time in its magnitude.

The within-subject variables were experimental condition (congruent, incongruent, or neutral), bar orientation (clockwise or counterclockwise), and bin (first to fifth). Here and in the following experiments, pairwise comparisons with the Newman–Keuls method were conducted whenever appropriate. The significance level was always set at .05.

In addition to the bin main effect, $F(4, 52) = 118.90, p < .001$, which was produced by the data subdivision, both experimental condition, $F(2, 26) = 4.36, p < .05$, and bar orientation, $F(1, 13) = 7.30, p < .05$, main effects were significant. Also, two 2-way interactions were significant: Experimental Condition $\times$ Bin, $F(8, 104) = 10.62, p < .001$, and Bar Orientation $\times$ Bin, $F(4, 52) = 5.50, p < .001$.

Pairwise comparisons revealed that RTs were faster for the congruent condition (286 ms) than for either the incongruent (294 ms) or the neutral (295 ms) condition, which did not differ. Thus, RT to initiate a grasping movement to an object was faster in response to the appearance of a congruent visual object. RT was slower when the movement was performed in response to either an incongruent or a neutral object. Therefore, in accordance

with our hypothesis, preparation of a grasping movement determined facilitation in the detection of a visual object the intrinsic properties of which were congruent with those of the to-be-grasped object (i.e., a motor–visual attentional effect).[1]

The post hoc analysis of the interaction between experimental condition and bin indicated that facilitation in the congruent condition depended on response speed (Figure 3). At the first three bins, the three experimental conditions did not differ. At the fourth bin, congruent condition RTs were faster than incongruent and neutral condition RTs, which did not differ. At the fifth bin, the congruent condition was faster than the incongruent condition, which in turn was faster than the neutral condition. A possible explanation for the lack of facilitation in the congruent condition at the faster bins is that when RT was very fast, participants responded before processing of the visual stimulus was completed. Note that, to perform the task correctly, it was enough for participants to respond to the sudden luminance increment. Thus, the motor–visual attentional effect could not occur because no match between object properties occurred. Another possible explanation is that, at the first bins, RTs were too fast for differences between conditions to emerge (i.e., a sort of floor effect).

The significant bar orientation main effect indicated that RTs were faster when the bar was oriented clockwise than when it was oriented counterclockwise (286 ms vs. 297 ms). A possible explanation is that the movement to grasp the clockwise-oriented bar was easier because it did not require shoulder abduction and elbow rising.

As clarified by the post hoc analysis, the Bar Orientation $\times$ Bin interaction showed that grasping movements directed to the clockwise bar were faster than those directed to the counterclockwise bar only at the fourth and fifth bins. Perhaps that, too, was a floor effect: RTs at the faster bins were too fast for the difference between the two grasping movements to manifest itself.

Finally, it must be noted that the facilitation observed on congruent trials may have been due, at least in part, to the influence of visual stimuli on the execution of congruent grasping movements. As mentioned in the introduction, visual presentation of a graspable object decreases the time to initiate a grasping movement that is congruent with the object's intrinsic properties (visuomotor priming effect; Craighero et al., 1996, 1998). Because RT for grasping indexes both the speed of processing the visual object (influenced by a motor–visual attentional effect) and the readiness to grasp the real object (influenced by a visuomotor priming effect), the two effects cannot be unconfounded

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[1] Responses on incongruent trials were not statistically different from those on neutral trials. Both response types were slower than those on congruent trials. However, concluding that attentional benefits occur in the absence of attentional costs is unwarranted. As was the case with the object presented on incongruent trials, the visual object presented on neutral trials did not share visual properties with the one to be grasped. From this point of view, neutral and incongruent trials were equivalent, and thus the issue of costs is in need of further exploration.

Table 1
Experiment 1: Grasping Movement Reaction Times (in Milliseconds)

Bin	Clockwise			Counterclockwise		
	Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
1st	233 ± 9	234 ± 7	231 ± 11	238 ± 7	240 ± 7	239 ± 10
2nd	263 ± 6	265 ± 6	265 ± 7	268 ± 5	269 ± 5	266 ± 7
3rd	277 ± 7	282 ± 8	284 ± 7	284 ± 5	289 ± 6	286 ± 6
4th	298 ± 8	300 ± 8	307 ± 10	303 ± 7	318 ± 9	310 ± 8
5th	339 ± 11	351 ± 12	368 ± 16	355 ± 11	387 ± 15	395 ± 16
Overall	282 ± 7	286 ± 7	291 ± 9	290 ± 6	301 ± 7	299 ± 8

Note. Values are means ($\pm SE$).

when only hand responses are used. This confounding was eliminated in Experiments 4 and 5.

Error analysis. Anticipation, retardation, and retardation in execution error rates were 3.4% each, whereas the wrong movement error rate was 0.6%. The latter errors were not analyzed. The other types of errors were subjected to separate ANOVAs identical to that performed on the RT data. No variable or interaction was significant for anticipation errors or for retardation in execution errors.

In the case of retardation errors, the bar orientation main effect, $F(1, 13) = 7.74$, $p < .05$, reached significance. Retardation errors were observed less frequently when the orientation of the bar to be grasped was clockwise. This is in accordance with the RT results. The movement required to grasp the clockwise bar is probably easier than that required to grasp the counterclockwise bar.

Experiment 2

Experiment 1 showed that RT to grasp an object was faster when the movement was executed in response to the appearance of a congruent visual object. The explanation we proposed was that the effect was essentially due to the fact that motor preparation facilitated detection of the visual object.

There is, however, an alternative explanation. Because the participants could not see the object they were instructed to grasp, they might have formed a visual image of it before the go signal was presented. When the image was congruent with the go signal, it might have produced a priming effect on the visual stimulus. However, whereas it is a well-established fact that perception primes imagery, whether imagery can prime perception is disputed (see, e.g., the review in V. Bruce, 1996). Although the alternative explanation did not seem to be very likely, it was nevertheless tested in Experiment 2.

Experiment 2 was identical to Experiment 1, except for the visual objects. The go signal was a drawing of a pencil that had the same orientations as the bar used in Experiment 1 (the size and the shape of the pencil could vary; see Figure 2B). The pencil-like stimulus, however, because of its

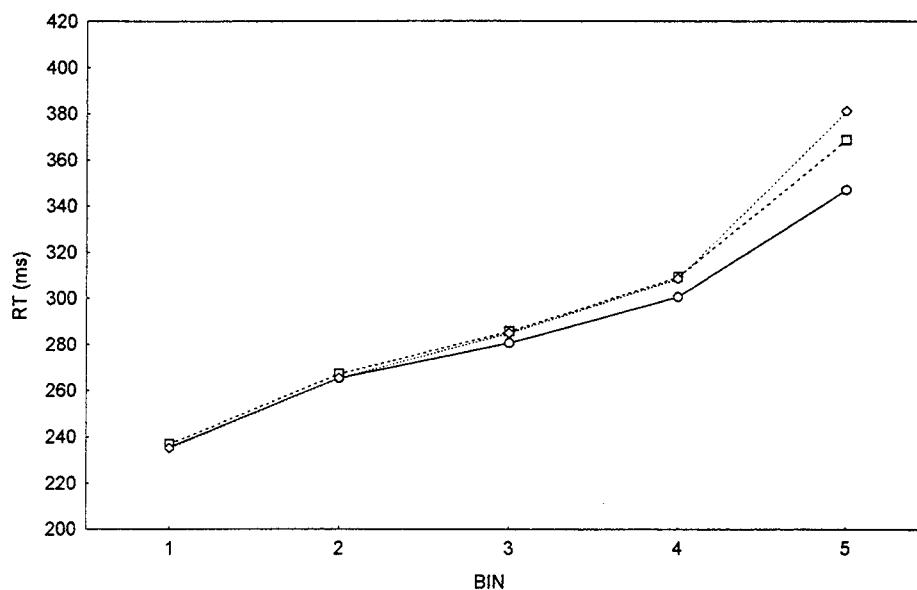*Figure 3.* Experiment 1: Experimental Condition × Bin interaction. The presence of facilitation in the congruent condition depended on response speed (solid line: congruent condition; dashed line: incongruent condition; dotted line: neutral condition). RT = reaction time.

dimensions (long pencil) or because of the presence of the two tips (short pencil), did not "afford" the same grasping movement as the bar did. Absence of an RT reduction in the congruent condition (same orientation for the to-be-grasped bar and the pencil) would confirm that what mattered in Experiment 1 was the relation between the motor program necessary to grasp the bar and the graspability properties of the visual stimulus. In contrast, the presence of an RT reduction would suggest that what mattered in Experiment 1 was congruency between the orientation of the mental visual image of the to-be-grasped bar and the orientation of the visual object.

Method

Participants. Fourteen students at the University of Parma between the ages of 20 and 25 years served as participants. They were selected as before.

Apparatus, stimuli, and procedure. The apparatus was the same as in the previous experiment. Participants were randomly assigned to two groups. The only difference between the two groups was the type of go signal to which they had to respond by executing the grasping movement to the bar described in Experiment 1.

The go signals consisted of the presentation, around the fixation cross, of a pencil-like stimulus rotated 45° clockwise on 50% of trials and rotated 45° counterclockwise on 50% of trials. The two go signals differed in size and color. One pencil-like stimulus was 16° × 1° (much longer and thinner than the visual bar used in Experiment 1; see Figure 2B, right) and was black and yellow. The other pencil-like stimulus was 6° × 2° (same dimensions as the visual bar used in Experiment 1; see Figure 2A and Figure 2B, left) and was red and blue. The background was always dark gray.

The procedure was the same as in the previous experiment, apart from the absence of neutral trials. In particular, there were two experimental conditions: congruent (same orientation for the pencil-like stimulus and the bar) and incongruent (different orientations). For each bar orientation, the number of trials for the two conditions was identical (40 trials each). Every participant was tested in one experimental session that comprised 160 randomized trials and was preceded by about 30 practice trials.

Results and Discussion

RT analysis. Mean RTs for each condition are shown in Table 2. An ANOVA was performed on mean RTs calculated for the first to the fifth bin of the rank-ordered raw data, separately for each bar orientation, each experimental condition, and each type of visual object.

The within-subject variables were experimental condition (congruent or incongruent), bar orientation (clockwise or counterclockwise), and bin (first to fifth). The between-subjects variable was size of the pencil-like stimulus (long or short).

The significant sources were the main effects of bin, $F(4, 48) = 88.32$, $p < .001$, and stimulus size, $F(1, 12) = 10.92$, $p < .01$, and the two-way interaction between stimulus size and bin, $F(4, 48) = 4.52$, $p < .01$. No sources involving experimental condition were significant.

RTs were faster in response to the short stimulus (252 ms) than in response to the long stimulus (330 ms). A possible explanation is the different perceptual salience of the two stimuli resulting from their different colors. In addition, luminance around the fixation point was much greater for the shorter than the longer pencil. Although the interaction between pencil size and bin was significant, the post hoc test showed that the effect was present at all bins.

Error analysis. All four types of errors (anticipations, retardations, retardations in execution, and wrong movements) were encountered very rarely, each being present on fewer than 0.7% of trials. Errors were not submitted to a statistical analysis.

Combined analysis for Experiment 1 and Experiment 2. The lack of significance for the experimental condition main effect, as well as the absence of significant interactions with this variable, showed that the mere congruence between orientation of the bar and orientation of the visual object was not sufficient to speed up RT. To exclude the possibility of a Type II error, we performed a further ANOVA in which the within-subject variable was experimental condition (congruent or incongruent) and the between-subjects variable was experiment (Experiment 1 or Experiment 2).

The experimental condition main effect, $F(1, 26) = 9.64$, $p < .01$, was significant, the congruent condition (288 ms) being faster than the incongruent condition (293 ms). The post hoc analysis performed on the interaction, $F(1, 26) = 3.45$, $p = .07$, confirmed that, in Experiment 1, the congruent condition (286 ms) was faster than the incongruent condition (294 ms); in Experiment 2, the two conditions were identical (290 ms vs. 291 ms).

Table 2
Experiment 2: Grasping Movement Reaction Times (in Milliseconds)

	Long				Short			
	Clockwise		Counterclockwise		Clockwise		Counterclockwise	
Bin	C	I	C	I	C	I	C	I
1st	249 ± 11	244 ± 10	252 ± 14	244 ± 10	196 ± 7	200 ± 8	204 ± 11	203 ± 11
2nd	282 ± 13	284 ± 13	287 ± 14	282 ± 13	218 ± 9	218 ± 9	228 ± 15	224 ± 14
3rd	302 ± 15	309 ± 14	321 ± 16	306 ± 16	235 ± 10	234 ± 11	247 ± 16	243 ± 16
4th	332 ± 17	347 ± 17	358 ± 23	348 ± 23	256 ± 14	258 ± 15	274 ± 21	273 ± 22
5th	436 ± 24	484 ± 37	458 ± 42	467 ± 38	316 ± 25	348 ± 42	346 ± 30	331 ± 32
Overall	320 ± 15	334 ± 16	334 ± 20	329 ± 19	244 ± 12	252 ± 13	260 ± 18	255 ± 19

Note. Values are means (±*SE*). C = congruent; I = incongruent.

These results indicated that, to produce an RT reduction in a grasping response, the visual object must share those properties that determine the type of grasping that is best suited to the real object. In the case of the experiments reported here, the visual bar shared these critical properties with the real bar, whereas the visual pencil did not.

Experiment 3

A weakness of Experiment 2 was that the visual stimuli (pencils), although sharing the orientation with the object to be grasped, were much different in meaning from it. Thus, whereas in the first experiment the bar used as a visual stimulus could, at least in theory, evoke a visual image congruent with the manipulandum and thus facilitate the response, the pencils could not evoke a congruent image because of their meaning. Thus, one might claim that the lack of facilitation in Experiment 2 was not due to the different graspability properties of the visual bar and the pencils.

To overcome this difficulty, in Experiment 3 we presented as visual stimuli two bars, but, unlike in Experiment 1, the tips of the bars were not flat but could be either concave (i.e., easy to grasp) or convex (i.e., hard to grasp). The prediction was that if a congruent visual image produced facilitation, the results of this experiment should replicate those of Experiment 1, regardless of the shape of the bar. In contrast, if potential graspability of the visual stimulus was responsible for the congruence effect, facilitation should be present with the concave bar but not with the convex bar.

Method

Participants. Thirteen students at the University of Parma between the ages of 20 and 22 years served as participants. All were right-handed, had normal or corrected-to-normal visual acuity, and were naive as to the purposes of the experiment. None had taken part in the previous experiments.

Apparatus, stimuli, and procedure. The apparatus was the same as in Experiments 1 and 2. The go signal consisted of one of four pictures (white lines on a black background) displayed around a fixation cross (cross arm, 0.5°). As shown in Figure 4, they were two polygons, one convex and the other concave. Each polygon had its longer axis rotated 45° clockwise in one picture and 45° counterclockwise in another picture. Each of the four pictures was presented randomly on an equal number of trials, and participants were explicitly instructed to execute the response while disregarding the specific shape of the go signal.

The response consisted of grasping as fast as possible the same bar used in the previous experiments. On 50% of trials, the bar orientation was 45° counterclockwise with respect to the sagittal plane of the participant's body; the orientation was 45° clockwise on the remaining trials. The orientation of the bar changed randomly trial by trial, and participants were informed about it at the beginning of each trial, as in the previous experiments. The procedure was the same as in Experiments 1 and 2.

For each orientation of the to-be-grasped bar, there were four experimental conditions: concave–congruent condition (the go signal was a concave polygon the orientation of which matched the orientation of the bar), concave–incongruent condition (the go signal was a concave polygon the orientation of which did not match the orientation of the bar), convex–congruent condition (the
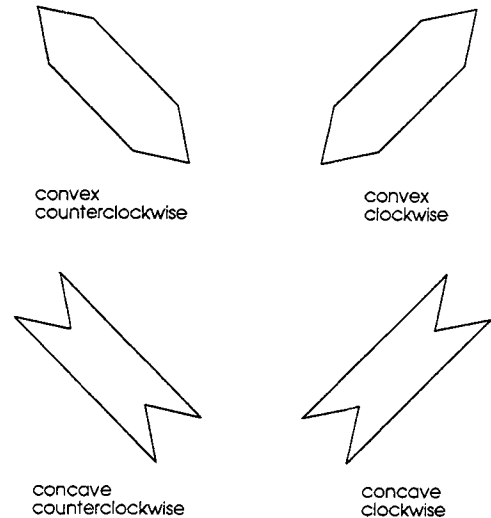

Figure 4. Visual stimuli presented in Experiment 3.

go signal was a convex polygon the orientation of which matched the orientation of the bar), and convex–incongruent condition (the go signal was a convex polygon the orientation of which did not match the orientation of the bar). For each bar orientation, the number of trials in each condition was identical (20 trials each).

Every participant was tested in one experimental session that comprised 160 randomized trials and was preceded by about 30 practice trials.

Results and Discussion

RT analysis. The mean RTs for each condition are shown in Table 3. An ANOVA was performed on mean RTs calculated for the first to the fifth bin of the rank-ordered raw data, separately for each bar orientation and each experimental condition.

The within-subject variables were type of polygon (concave or convex), polygon orientation (clockwise or counterclockwise), bar orientation (clockwise or counterclockwise), and bin (first to fifth). The significant sources were the main effect of bin, $F(4, 48) = 179.20, p < .01$, and the three-way Type of Polygon × Polygon Orientation × Bar Orientation interaction, $F(1, 12) = 9.53, p < .01$.

Pairwise comparisons of the three-way interaction revealed that concave–congruent condition RTs were faster than convex–congruent condition RTs for both to-be-grasped bar orientations (clockwise bar orientation: concave–clockwise picture, 263 ms, vs. convex–clockwise picture, 273 ms; counterclockwise bar orientation: concave–counterclockwise picture, 271 ms, vs. convex–counterclockwise picture, 282 ms; Figure 5). This result is in accord with the hypothesis that motor preparation facilitates detection of visual objects that "afford" the prepared grasping. In effect, whereas in the concave–congruent condition the picture could be "grasped" with the prepared grasping by inserting the fingers between the tips, in the convex–congruent condition the picture could not be "grasped" with the same movement because of the presence of the two sharp tips. In either condition, the orientation of the picture was congruent

Table 3
Experiment 3: Grasping Movement Reaction Times (in Milliseconds)

| Bin | Clockwise | | | | Counterclockwise | | | |
| | Concave | | Convex | | Concave | | Convex | |
	Clock-wise	Counter-clockwise	Clock-wise	Counter-clockwise	Clock-wise	Counter-clockwise	Clock-wise	Counter-clockwise
1st	216 ± 9	222 ± 9	226 ± 8	221 ± 9	227 ± 9	226 ± 8	231 ± 11	231 ± 10
2nd	243 ± 9	246 ± 9	251 ± 9	247 ± 10	252 ± 11	247 ± 9	252 ± 11	256 ± 12
3rd	257 ± 9	262 ± 9	266 ± 10	264 ± 9	269 ± 11	264 ± 9	267 ± 12	276 ± 13
4th	278 ± 10	285 ± 10	286 ± 10	285 ± 10	290 ± 12	283 ± 10	287 ± 13	294 ± 14
5th	322 ± 15	328 ± 10	335 ± 14	345 ± 18	335 ± 15	333 ± 16	332 ± 17	353 ± 17
Overall	263 ± 9	269 ± 9	273 ± 9	272 ± 11	275 ± 11	271 ± 10	274 ± 12	282 ± 13

Note. Values are means ($\pm SE$).

with that of the bar, and the picture was different from the bar. Thus, the results could not be due to orientation congruency or to the fact that the stimulus and the to-be-grasped object were identical.

Also, pairwise comparisons revealed that, for the counterclockwise bar orientation, the convex–congruent condition was significantly slower (282 ms) than the incongruent conditions (274 ms for both the concave–incongruent condition and the convex–incongruent conditions). Particularly

interesting is the fact that the convex–congruent condition was significantly slower than the convex–incongruent condition. Note that, whereas the convex polygon could be "grasped" only on its shorter axis, the concave polygon could be "grasped" both on its longer axis and on its shorter axis (the finger opposition space of the prepared grasping is less important in determining the motor–visual attentional effect than other grasping characteristics; Fadiga & Craighero, personal communication, 1997). Thus, the only condi-
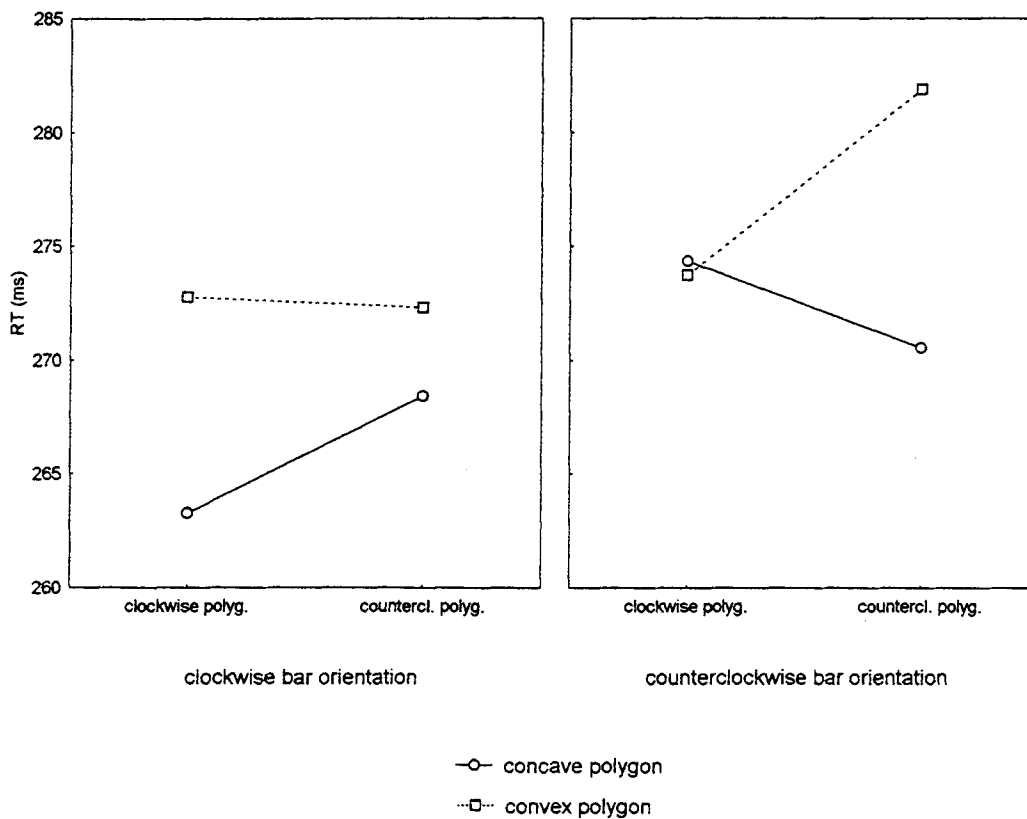

Figure 5. Experiment 3: Three-way interaction among type of polygon (polyg.), polygon orientation, and bar orientation. For either bar orientation, reaction times (RTs) in the concave–congruent condition were faster than RTs in the convex–congruent condition. countercl. = counterclockwise.

tion that could not be facilitated by grasping preparation was the convex–congruent one. In addition, pairwise comparisons revealed that when the bar was oriented clockwise, the convex–incongruent condition (272 ms) was significantly slower than the concave–incongruent condition (268 ms).

Error analysis. Anticipation, retardation, retardation in execution, and wrong movement error rates were, respectively, 6.8%, 2.6%, 5.9%, and 0.3%. The latter were not analyzed. The other types of errors were subjected to separate ANOVAs with the same within-subject variables considered in the RT analysis. No variable or interaction was significant for anticipation errors.

In the case of retardation errors, the type of polygon main effect, $F(1, 12) = 4.87$, $p < .05$, reached significance. Retardation errors were observed less frequently when the go signal was a concave polygon. This is in accordance with the RT results. Preparation of grasping facilitated detection of visual objects that shared graspability properties with the prepared movement. As we discussed earlier, the concave polygon had a greater degree of congruency with the grasping of the bar than the convex one had.

For retardation in execution errors, the bar orientation main effect, $F(1, 12) = 12.42$, $p < .001$, reached significance. This type of error was observed more frequently when bar orientation was counterclockwise. This result confirms that grasping the clockwise bar is easier than grasping the counterclockwise one (see also Experiment 1).

Experiment 4

Experiment 4 was conducted to investigate whether the facilitation found in Experiment 1 is limited to the detection of stimuli for subsequent hand movements or is present also in the case of responses executed with other effectors. Obtaining this result with effectors other than the hand would be critical for showing that facilitation is due to improving object detection by a congruent motor program. If the effect occurred only with manual responses, facilitation might be due to priming of the motor program by the visual object, as previously demonstrated by Craighero et al. (1996, 1998).

The rationale of Experiment 4 (and of Experiment 5) was the following. Participants were instructed to prepare a grasping response to an object (a bar, as usual). On most trials, the grasping response was executed when the go signal (again, a bar) appeared. Thus, on most trials Experiment 4 was identical to Experiment 1. On some trials, however, the go signal instructed the participants to withhold the prepared grasping response and to execute instead a switch-press response with the foot. If preparing the grasping response facilitates processing of a congruent visual object, then facilitation on congruent trials should manifest itself with the switch-press response as well. In brief, the main purpose of Experiment 4 (and of Experiment 5) was to show that the effect found in Experiment 1 was due to a motor–visual attentional effect rather than to visuomotor priming.

To this aim, two changes were made to the procedure of

Experiment 1. The simple detection task was replaced by a discrimination task. A discrimination task requires complete processing of the visual stimulus and does not allow the participant merely to respond to a sudden luminance increment. The second and most critical change was that one of the responses was a foot switch press that was executed in place of the prepared grasping, presumably after inhibiting it.

Participants were instructed to prepare a grasping movement to one of the two bars and, on two thirds of trials, to respond to the go signal by executing the grasping movement. On the remaining one third of trials, they had to inhibit the prepared grasping movement and respond by pressing a switch with their right foot. If preparation of a motor program reduces the time required to respond to a visual stimulus the intrinsic properties of which match those of the to-be-grasped object (i.e., the motor–visual effect), a time reduction in reacting to the visual stimulus should occur, regardless of the effector that is used to execute the response.

Method

Participants. Eighteen students at the University of Parma between the ages of 20 and 25 years served as participants. All were right-handed, had normal or corrected-to-normal visual acuity, were naive as to the purposes of the experiment, and had not participated in the previous experiments.

Apparatus and stimuli. The apparatus was the same as in the previous experiments. As in the previous experiments, the bar that was to be grasped (6 × 2.5 cm) was present on each trial. On 50% of trials, the bar orientation was 45° counterclockwise; the orientation was 45° clockwise for the remaining trials.

The go signal was the presentation, around the fixation cross, of a picture (white lines on a black background) that was drawn from two sets differing in size but not shape or orientation. Set 1 consisted of a rectangle, 6° × 2°, rotated 45° clockwise; a rectangle, 6° × 2°, rotated 45° counterclockwise; and a circle (diameter: 3°). Set 2 consisted of a rectangle, 3.6° × 1.2°, rotated 45° clockwise; a rectangle, 3.6° × 1.2°, rotated 45° counterclockwise; and a circle (diameter: 1.8°).

Two different responses were required, depending on the type of go signal. One was to execute the prepared grasping movement to the bar, and the other was to press, with the right foot, a switch (diameter: 5 cm) positioned on the floor. Participants were randomly assigned to two groups given different instructions. Those in Group A had to respond to the Set 1 go signal by executing the grasping movement (two thirds of trials) and to the Set 2 go signal by pressing the switch (one third of trials). For those in Group B, the instructions were reversed; that is, they had to respond to the Set 1 go signal by pressing the switch (one third of trials) and to the Set 2 go signal by executing the grasping movement (two thirds of trials).

Procedure. As in the previous experiments, participants were instructed to prepare a grasping movement congruent with the cued bar orientation, before starting the trial by pressing the home position switch with their right hand. Bar orientation was randomly changed trial by trial, and orientation was signaled at the beginning of each trial on the computer screen.

On presentation of the go signal, participants had to discriminate its size and select the appropriate response (i.e., the grasping movement or the foot switch press), depending on instructions. If the required response was to press the switch, they had to keep pressing the home position switch until the end of the trial.

Table 4
Experiment 4: Foot Switch-Press Reaction Times (in Milliseconds)

Bin	Clockwise			Counterclockwise		
	Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
1st	402 ± 16	421 ± 16	402 ± 16	419 ± 20	420 ± 17	426 ± 17
2nd	458 ± 19	486 ± 19	473 ± 20	479 ± 23	480 ± 19	484 ± 20
3rd	504 ± 19	535 ± 21	531 ± 22	524 ± 24	519 ± 20	533 ± 23
4th	560 ± 19	594 ± 23	576 ± 23	573 ± 26	573 ± 23	592 ± 24
5th	659 ± 22	698 ± 28	695 ± 27	674 ± 27	686 ± 22	701 ± 26
Overall	517 ± 18	547 ± 20	535 ± 20	534 ± 24	536 ± 20	547 ± 21

Note. Values are means ($\pm SE$).

For each type of response, there were three experimental conditions: congruent, incongruent, and neutral. The number of congruent, incongruent, and neutral trials was the same. RT was the time between the go signal and the release of the home position switch (grasping movement) or the pressure of the switch (switch press).

In addition to the errors already described for the previous experiments, anticipation and retardation errors could occur because of an inappropriate switch press. Anticipation errors were RTs shorter than 120 ms. Retardation errors were RTs longer than 1,000 ms. Also, a wrong type of response error was recorded when participants executed a grasping movement instead of the switch press, or vice versa. It is important to note that very few grasping errors were made (as described subsequently). This showed that the correct grasping movement was prepared before initiation of the trial, even though grasping was not always required. Each participant was tested in one experimental session that comprised 360 randomized trials (240 trials for the grasping response and 120 trials for the switch-press response) and was preceded by about 30 practice trials.

Results and Discussion

Mean RTs for switch presses are shown in Table 4, and those for grasping movements are shown in Table 5. Data for the two types of responses were analyzed separately.

RT analysis for switch presses. An ANOVA was performed on mean RTs calculated for the first to the fifth bin of the rank-ordered raw data, separately for each bar orientation, each experimental condition, and each type of visual object. The within-subject variables were experimental condition (congruent, incongruent, or neutral), bar orientation (clockwise or counterclockwise), and bin (first to fifth).

In addition to the bin main effect, $F(4, 68) = 422.81, p < .001$, the experimental condition main effect was significant, $F(2, 34) = 3.69, p < .05$. Also, two 2-way interactions were significant: Experimental Condition × Bar Orientation, $F(2, 34) = 4.77, p < .05$, and Experimental Condition × Bin, $F(8, 136) = 2.05, p < .05$.

The post hoc tests revealed that RTs were faster in the congruent condition (525 ms) than in either the incongruent (541 ms) or the neutral (541 ms) condition. The RT reduction in the foot switch-press response no doubt reflects a facilitation in the detection of visual objects that was produced by preparation of a congruent grasping movement. This indicates that a motor–visual attentional effect initiated in a grasping circuit involved effectors other than the hand.

The post hoc tests performed on the interaction between experimental condition and bin showed that the motor–visual attentional effect was present at all bins except the first one. Perhaps there was a floor effect when responses were very fast.

The significance of the interaction between experimental condition and bar orientation was due to the fact that when the bar was oriented counterclockwise, the three experimental conditions did not differ (congruent condition: 534 ms; incongruent condition: 536 ms; and neutral condition: 547 ms), whereas when the bar was oriented clockwise, the congruent condition was faster than either the incongruent or the neutral condition, which did not differ (congruent condition: 517 ms; incongruent condition: 547 ms; and neutral condition: 535 ms; see Figure 6). A possible explanation is that of a more compatible postural relation between preparation of a clockwise grasping movement with the right

Table 5
Experiment 4: Grasping Movement Reaction Times (in Milliseconds)

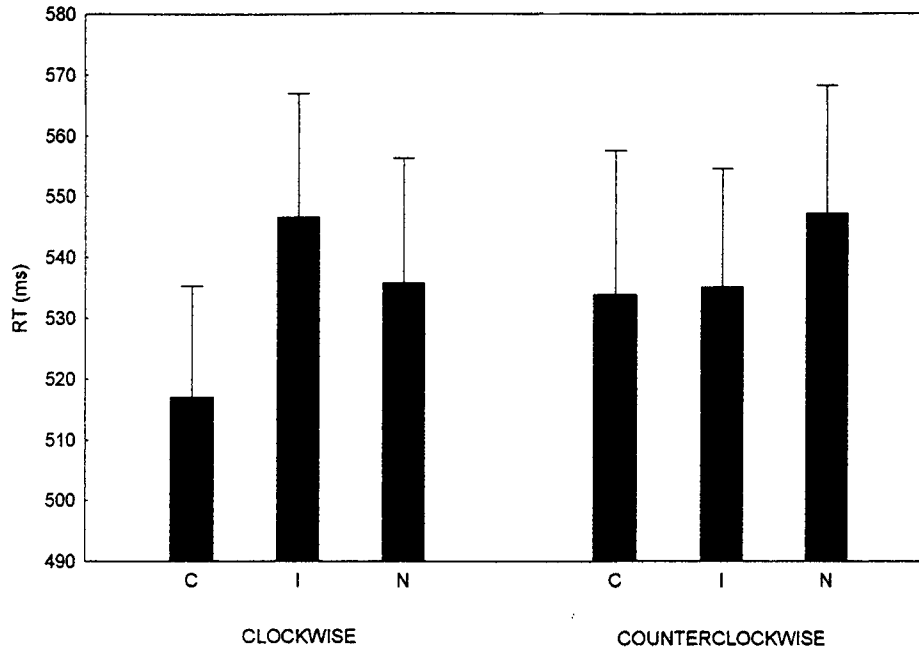| Bin	Clockwise			Counterclockwise		
	Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
1st	343 ± 8	364 ± 10	365 ± 7	349 ± 7	384 ± 10	373 ± 9
2nd	398 ± 8	426 ± 12	420 ± 9	403 ± 7	436 ± 9	427 ± 8
3rd	436 ± 9	464 ± 13	461 ± 11	438 ± 8	475 ± 10	466 ± 11
4th	479 ± 10	511 ± 14	512 ± 13	481 ± 10	523 ± 11	518 ± 14
5th	578 ± 17	603 ± 19	628 ± 19	570 ± 13	615 ± 16	646 ± 19
Overall	447 ± 9	474 ± 12	477 ± 11	448 ± 8	487 ± 10	486 ± 11

Note. Values are means ($\pm SE$).

Figure 6. Experiment 4: Two-way interaction between experimental condition and bar orientation for foot switch-press responses. Note that switch-press reaction time (RT) in the congruent condition was faster than in either the incongruent or in the neutral condition when the prepared grasping was to the clockwise-oriented bar. Vertical lines represent standard errors. C = congruent condition; I = incongruent condition; N = neutral condition.

hand and execution of a switch press with the right foot. As a result, the facilitation effect of the motor program on the discrimination of the visual object manifested itself only for the clockwise orientation. Note that the congruent condition after preparation of a clockwise grasping movement was faster than every other condition. Experiment 5 dealt with this issue.

Error analysis for switch presses. Anticipation and retardation error rates were below 0.8% and were not analyzed. Wrong type of response errors occurred on 12.2% of trials and were submitted to an ANOVA.

No sources of significance were found, but a post hoc analysis was performed on the interaction between experimental condition and bar orientation, $F(2, 34) = 2.93$, $p = .07$. Grasping responses were executed in place of switch-press responses more frequently on congruent trials when the prepared grasping was toward the clockwise-oriented bar than in all other conditions (all $ps < .05$). Preparation of a clockwise grasping, being easier than preparation of a counterclockwise grasping, probably was more difficult to inhibit when the go signal was a congruent visual stimulus. This suggests that congruence between the intrinsic properties of the object to be grasped and those of the visual stimulus has the tendency to automatically elicit a grasping response.

RT analysis for grasping movements. An ANOVA was performed on mean RTs calculated for the first to the fifth bin. As before, the within-subject variables were experimental condition (congruent, incongruent, or neutral), bar orien-

tation (clockwise or counterclockwise), and bin (first to fifth).

Needless to say, the bin main effect was significant, $F(4, 68) = 374.57$, $p < .001$. In addition, significant sources were the experimental condition main effect, $F(2, 34) = 26.20$, $p < .001$, and the two-way interaction between experimental condition and bin, $F(8, 136) = 8.08$, $p < .001$.

The post hoc analysis on the experimental condition main effect revealed that congruent condition RTs (447 ms) were faster than either incongruent condition (480 ms) or neutral condition (482 ms) RTs. Thus, the results obtained with a discrimination task replicated those obtained in Experiment 1 with a detection task: Preparation of a grasping movement to a specific object reduced grasping movement RTs in response to a congruent visual object.

The post hoc analysis on the interaction between experimental condition and bin revealed that, at all bins, the congruent condition was faster than either the incongruent or the neutral condition. At the first four bins, the incongruent and neutral condition did not differ, whereas, at the fifth bin, the incongruent condition was faster than the neutral condition (Figure 7). This result showed that, in a discrimination task in which a complete processing of the visual stimuli is required and the RTs are longer than in a detection task (Experiment 1), the facilitation of congruent RTs is independent of response speed.

Error analysis for grasping movements. Anticipation and retardation error rates were below 0.7%. Retardation in execution, wrong movement, and wrong type of response
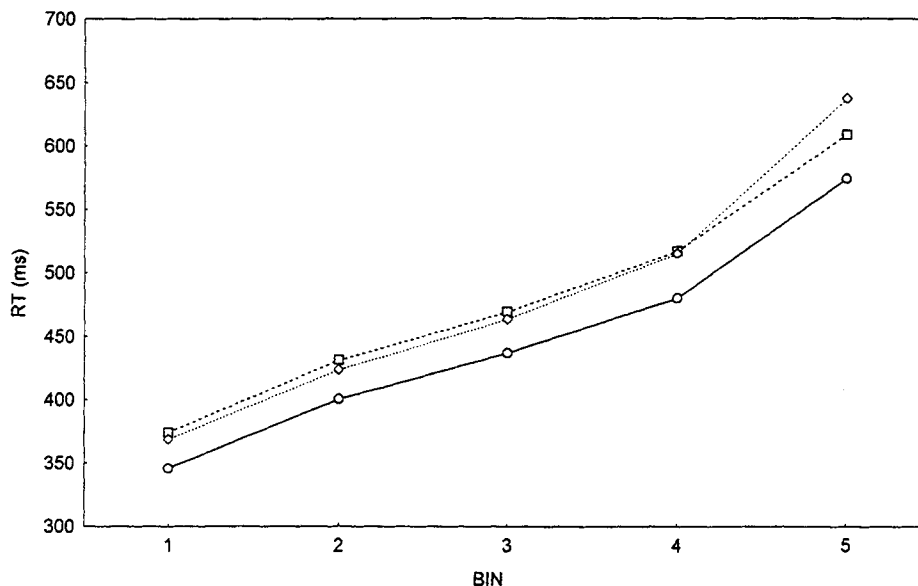
Figure 7. Experiment 4: Two-way interaction between experimental condition and bin for grasping responses. The congruent condition was faster than either the incongruent or the neutral condition for all bins (solid line: congruent condition; dashed line: incongruent condition; dotted line: neutral condition). RT = reaction time.

error rates were 2.2%, 1.8%, and 1.64%, respectively. The last three types of error were submitted to separate ANOVAs.

No variable or interaction was significant for retardation in execution errors. For wrong movement errors, the experimental condition main effect, $F(2, 34) = 13.43, p < .001$, was significant. A post hoc analysis showed that wrong grasping responses (i.e., to the clockwise-oriented bar instead of the counterclockwise bar, or vice versa) were observed more frequently on incongruent trials than on congruent and neutral trials (both $ps < .01$). This showed the absence of a speed–accuracy trade-off. Responses given on congruent trials were faster and more accurate than responses given on incongruent trials. This result confirmed the presence of a visuomotor priming effect (Craighero et al., 1996, 1998). The mere sight of a visual stimulus induces the participant to execute a congruently oriented grasping movement.

For wrong type of response errors, the experimental condition main effect, $F(2, 34) = 3.41, p < .05$, and the interaction between experimental condition and bar orientation, $F(2, 34) = 3.41, p < .05$, were significant. The post hoc analysis showed that switch-press responses in place of the grasping responses were given more frequently on neutral trials than on congruent and incongruent trials (both $ps < .05$), especially when the prepared grasping response was directed to the clockwise-oriented bar (clockwise vs. counterclockwise, $p < .05$ on neutral trials).

Experiment 5

The purpose of Experiment 5 was to replicate the motor–visual effect with a response that could not be influenced by visuomotor priming (as in Experiment 1) or

affected by a postural relation with the grasping movement (as in Experiment 4). Therefore, blinking with both eyelids—that is, a nonlateralized response—was used.

Method

Participants. Eighteen students at the University of Parma between the ages of 20 and 25 years served as participants. All were right-handed, had normal or corrected-to-normal visual acuity, and were naive as to the purposes of the experiment. None had taken part in the previous experiments.

Apparatus and stimuli. The apparatus and the stimuli were the same as in Experiment 4. Two responses were required: grasping the bar or blinking with both eyelids. Execution of the blink was recorded by an infrared oculometer (Bach, Bouis, & Fischer, 1983).

Procedure. The procedure was the same as in Experiment 4, except that the blink replaced the switch press. On presentation of the go signal, participants had to discriminate its size and execute the grasping movement (50% of trials) or blink (50% of trials), depending on instructions. If the required response was to blink, they had to maintain the home position switch press until the end of the trial.

For both responses, there were three experimental conditions: congruent, incongruent, and neutral. For each type of response, the number of congruent, incongruent, and neutral trials was the same.

RT was the time between the go signal and initiation of the grasping movement or of blinking. The recorded errors were the same as in Experiment 4. Each participant was tested in one experimental session that comprised 480 completely randomized trials (240 trials for grasping movements and 240 trials for blinking) and was preceded by about 30 practice trials.

Table 6

Experiment 5: Blinking Reaction Times (in Milliseconds)

Bin	Clockwise			Counterclockwise		
	Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
1st	328 ± 9	344 ± 9	330 ± 11	326 ± 10	337 ± 10	332 ± 11
2nd	377 ± 12	393 ± 12	383 ± 13	376 ± 12	387 ± 11	383 ± 13
3rd	419 ± 14	432 ± 13	419 ± 15	418 ± 14	421 ± 12	424 ± 16
4th	462 ± 16	481 ± 16	466 ± 19	469 ± 16	465 ± 14	470 ± 19
5th	561 ± 22	597 ± 25	561 ± 24	578 ± 22	575 ± 21	570 ± 24
Overall	429 ± 14	449 ± 14	432 ± 16	433 ± 14	437 ± 13	436 ± 16

Note. Values are means (±*SE*).

Results and Discussion

Mean RTs for blinking are shown in Table 6, and those for grasping movements are shown in Table 7. Data for the two responses were analyzed separately.

RT analysis for blinking. An ANOVA was performed on mean RTs calculated for the first to the fifth bin. The within-subject variables were the same as in Experiment 4. The bin main effect, $F(4, 60) = 321.06$, $p < .001$, and the two-way Experimental Condition × Bar Orientation interaction, $F(2, 30) = 4.79$, $p < .05$, were significant.

The post hoc analysis revealed that the significance of the Experimental Condition × Bar Orientation interaction (see Figure 8) was due to the fact that when bar orientation was counterclockwise, the three experimental conditions did not differ (congruent condition: 433 ms; incongruent condition: 437 ms; and neutral condition: 436 ms), whereas when bar orientation was clockwise, the congruent condition (429 ms) and the neutral condition (432 ms) were faster than the incongruent condition (450 ms). The congruent and neutral conditions did not differ. This indicated that the significant Experimental Condition × Bar Orientation interaction found in Experiment 4 was not simply attributable to a postural relation between the two movements. In fact, facilitation of the congruent condition was present only after preparation of a clockwise grasping movement, even though the response was a nonlateralized blink rather than a lateralized switch press. It is clear that congruence between the motor program and the to-be-discriminated visual object was effective only for the clockwise movement. Further evidence is needed to explain the difference between clock-

wise and counterclockwise movements. Note, however, that in Experiment 1, as well as for grasping responses in Experiments 4 and 5, the congruence effect was present for both movements.

Error analysis for blinking. Anticipation and retardation error rates were 1.5% and 0.6%, respectively, and were not analyzed. The wrong type of response error rate was 3.8%, and these errors were submitted to an ANOVA. No significant sources were found.

RT analysis for grasping movements. The usual ANOVA was performed on mean RTs calculated for the first to the fifth bin. The bin main effect, $F(4, 60) = 191.11$, $p < .001$; the experimental condition main effect, $F(2, 30) = 10.13$, $p < .001$; and the two-way interaction between experimental condition and bin, $F(8, 120) = 2.10$, $p < .05$, were significant.

The post hoc tests revealed that RTs for the congruent condition (440 ms) were faster than RTs for either the incongruent (464 ms) or the neutral (471 ms) condition, which did not differ. This pattern was present at every bin, although its magnitude changed (see Figure 9). These results replicated those of Experiment 4.

Error analysis for grasping movements. Retardation and retardation in execution error rates were below 0.6% and were not analyzed. Anticipation and wrong movement error rates were 1.8% each, and the wrong type of response error rate was 6.2%. They were submitted to separate ANOVAs. No sources of significance were found for anticipation or wrong type of response errors.

For wrong movement errors, the main effect of experimen-

Table 7

Experiment 5: Grasping Movement Reaction Times (in Milliseconds)

Bin	Clockwise			Counterclockwise		
	Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
1st	344 ± 11	361 ± 13	371 ± 13	342 ± 12	358 ± 14	366 ± 13
2nd	391 ± 12	414 ± 16	420 ± 15	395 ± 14	409 ± 15	417 ± 13
3rd	424 ± 15	449 ± 18	458 ± 19	428 ± 14	446 ± 17	450 ± 15
4th	467 ± 18	490 ± 20	503 ± 23	467 ± 17	489 ± 19	492 ± 20
5th	573 ± 25	618 ± 32	626 ± 31	561 ± 23	607 ± 32	605 ± 30
Overall	440 ± 16	466 ± 19	476 ± 20	439 ± 16	462 ± 19	466 ± 18

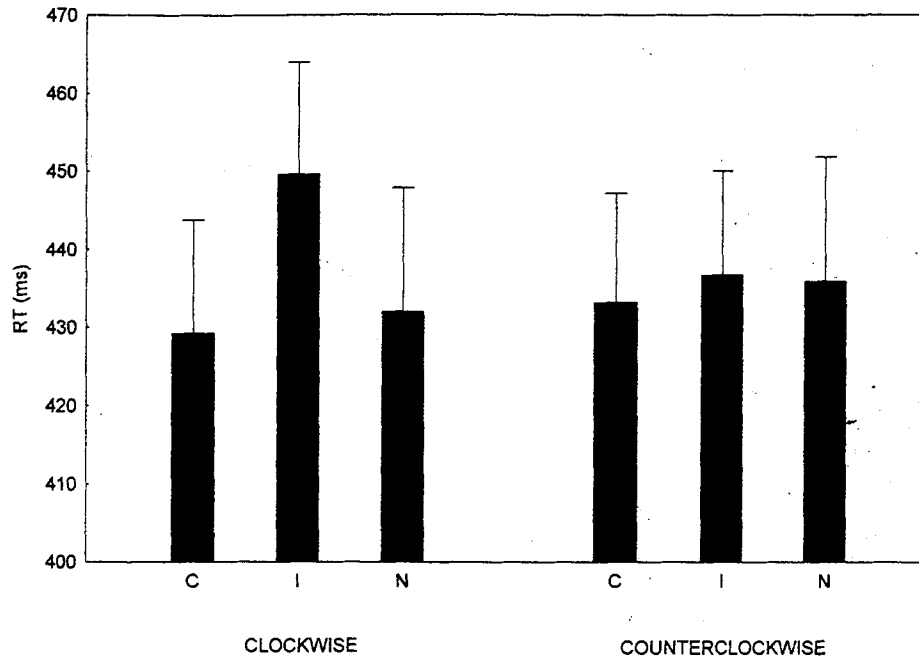*Note.* Values are means (±*SE*).

Figure 8. Experiment 5: Two-way interaction between experimental condition and bar orientation for blinking responses. Note that blinking reaction times (RTs) in the congruent and in the neutral condition were faster than in the incongruent condition when the prepared grasping was to the clockwise-oriented bar. Vertical lines represent standard errors. C = congruent condition; I = incongruent condition; N = neutral condition.

tal condition, $F(2, 30) = 5.97, p < .01$, was significant. A post hoc analysis showed that wrong grasping responses were observed more frequently on incongruent trials than on congruent and neutral trials (both $ps < .01$). These results replicated those obtained in the analysis of grasping response errors in Experiment 4. Also, they confirmed the absence of a speed–accuracy trade-off and the presence of a visuomotor priming effect for accuracy.
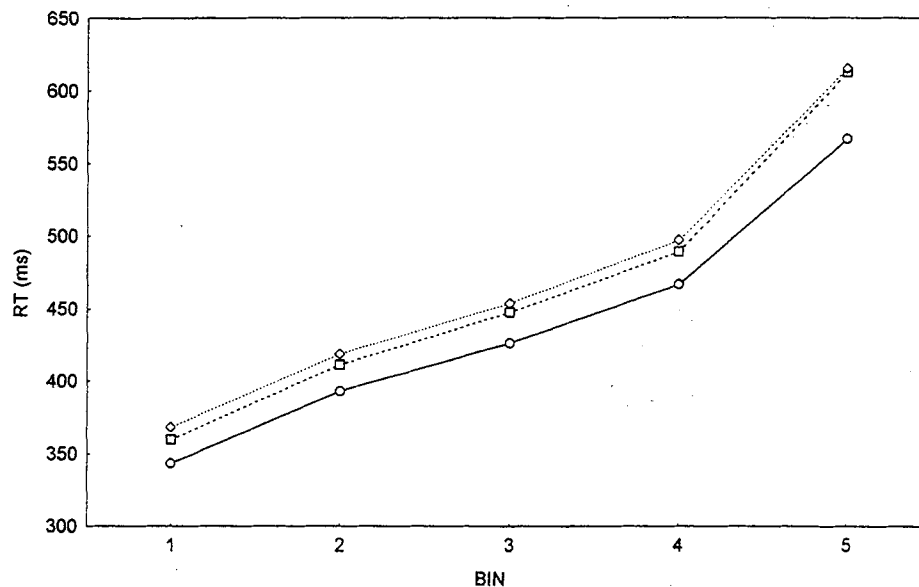

Figure 9. Experiment 5: Two-way interaction between experimental condition and bin for grasping responses. The congruent condition was faster than either the incongruent or the neutral condition for all bins (solid line: congruent condition; dashed line: incongruent condition; dotted line: neutral condition). RT = reaction time.

General Discussion

The aim of the present study was to examine whether the premotor theory of attention (e.g., Rizzolatti et al., 1987, 1994), originally formulated to account for orienting attention to spatial locations, could hold also for orienting attention to graspable objects. The basic claim of the premotor theory is that attention is a consequence of the activation of the circuits that mediate sensorimotor transformations, even in the absence of an overt action. In its original formulation, the premotor theory affirmed that spatial attention derives from endogenous or exogenous activation of the cortical oculomotor circuits. As a consequence, there is a facilitation in processing stimuli coming from that space sector toward which the oculomotor program is prepared.

The results of the present study indicate that the preparation of a grasping movement to a specific object reduces the time required to detect and discriminate a visual object the intrinsic properties of which match those of the object to be grasped. This effect was found when the required response was either the prepared grasping or the movement of another effector (i.e., the foot or the eyelids).

Before examining the implications of these findings for the premotor theory, we consider whether there are interpretations of the facilitation observed in the congruent condition alternative to the one that postulates a motor preparation. One possibility is that the congruent facilitation was due to a sort of priming evoked by the visual image of the to-be-grasped object on the visual stimulus that triggers the motor response. Although the existence of a priming effect of imagery on perception is disputed (V. Bruce, 1996), this possibility was empirically tested in Experiments 2 and 3. A visual priming effect should reveal itself specifically when stimulus and response share visual characteristics, such as (critical for the present work) orientation and identity. Experiment 2 examined the effect of mere orientation congruency between stimulus and response, and Experiment 3 assessed the effect of orientation congruency and identity between stimulus and response. Results showed that when the object to be grasped and the visual stimulus differed in their motor affordance, even if they shared orientation, facilitation for the congruent condition disappeared. This is clearly at odds with an interpretation of the facilitatory effect in terms of visual imagery, because a visual image of the to-be-grasped object should have been present in Experiments 1, 2, and 3.

Another possible interpretation of the facilitatory effect for congruent visual stimuli is that facilitation was due to visuomotor priming (Craighero et al., 1996, 1998) rather than motor–visual attentional effect. In other words, presentation of a stimulus having certain intrinsic properties facilitated grasping an object having the same intrinsic properties. This interpretation is basically consistent with current accounts of spatial stimulus–response (S-R) compatibility effects. It must be noted, however, that in the present study simple RTs were measured, which normally do not produce spatial S-R compatibility effects (Umiltà & Nicoletti, 1990). There are two main accounts of S-R compatibil-

ity: the dimensional overlap hypothesis (Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995) and the salient features hypothesis (Weeks & Proctor, 1990). The former maintains that when there is enough similarity between a task-relevant or task-irrelevant stimulus dimension and the relevant response dimension (i.e., the two dimensions overlap), the stimulus automatically activates its corresponding response. The latter maintains that similarity between the stimulus and the response dimension is based on salient features. At any rate, in either the dimensional overlap account or the salient features coding account, the overlap (i.e., similarity) between stimulus and response features is assumed to determine the speed of response in S-R paradigms.

In the present study, however, attributing the congruency effect to visuomotor priming or S-R compatibility is rather unlikely, at least as the main cause of the observed effect. In Experiments 4 and 5, participants responded to the go signal using an effector (i.e., the foot or the eyelids) different from the one that had been prepared for the grasping movement. Thus, response execution should have acquired no advantage from presentation of a visual object that was congruent only with the grasping movement. Yet, a facilitation effect also occurred in the case of foot or eyelid responses; this effect was solely attributable to the influence of the motor program on stimulus discrimination. These considerations rule out visuomotor priming, or S-R compatibility, as the main cause of the facilitation observed for the foot and eyelid responses in Experiments 4 and 5. It cannot be excluded, however, that in Experiment 1 (as well as for the grasping responses in Experiments 4 and 5) facilitation could have originated from visuomotor priming or S-R compatibility, especially in the case of slow responses, when the visual stimulus remained available for some time before the response was executed. It is interesting to note that, in Experiment 1, facilitation occurred only in the slower bin regions.

Taken together, these considerations indicate that preparation of a specifically oriented grasping movement facilitates visual processing of stimuli sharing the same intrinsic properties. The interpretation that we favor is in terms of an attentional effect determined by motor preparation. There is, however, another possible interpretation of at least a portion of the present results. Recently, Prinz and coworkers (Hommel, in press; Prinz, 1997) proposed a model according to which stimuli and responses are represented in the cognitive system as events and, therefore, coded in a commensurable format. The basic unit of this coding system is the "action concept." The action concept is the association between movement-producing and effect-produced patterns. The action-concept model does not distinguish between stimulus and response codes. Perception and action are seen as sensorimotor interactions extended over time. Both are mediated by action concepts and, hence, by the same kind of representation. "Stimulus codes" and "response codes" are used as labels to indicate the different roles the respective codes play in a given task context, not to indicate different kinds of codes. Thus, perceiving and acting are not alternating modes or functions but, in a sense, one and the same

thing. This theoretical stance predicts that whenever the stimulus code of an action concept is activated, the related response code is formed automatically; conversely, when the response code is activated, the related stimulus code is formed. The action-concept model has been applied with success to account for a series of phenomena, mostly in the field of S-R compatibility (Hommel, 1997; Müsseler & Hommel, 1997).

It is certainly possible to explain the findings of the present experiments within the framework of the action-concept model without invoking the premotor theory of attention. However, this can be done only for the condition in which the required response is the actual execution of the prepared grasping. In this case, activation of the action concept "grasp" facilitates the congruent responses and possibly interferes with incongruent responses. The action-concept model does not make specific claims about a possible role of an action concept in facilitating responses that are not part of it. Thus, the action-concept model cannot account for those conditions in which the required response was a foot or an eyelid response. In these conditions, it is necessary to refer to factors different from those postulated by the action-concept model. The premotor theory of attention accommodates perfectly well the latter result and is, in our opinion, the simplest way to explain also the facilitation of congruent responses during actual grasping execution. It is obvious, however, that for this condition, the action-concept model explanation cannot be ruled out.

There is a clear parallel between the facilitation resulting from the preparation of a grasping movement and that resulting from oculomotor programming. In the former case detection of a given object's graspability properties is facilitated, whereas in the latter case facilitation favors a specific spatial location.

This extension of the premotor theory from the oculomotor to the skeletomotor system is in accord with the notion that the dorsal stream inferior parietal lobule is the cortical region that codes visual information for the organization of actions directed toward specific space regions (and from which space perception most likely derives; see Rizzolatti et al., 1994), as well as the organization of actions that are based on nonspatial intrinsic object properties (Goodale & Milner, 1992; Goodale et al., 1991; Jeannerod et al., 1995; Rizzolatti et al., 1994).

The term *premotor,* used by Rizzolatti et al. (1987, 1994), necessarily restricts the scope of the premotor theory to the dorsal stream. However, studies conducted by Chelazzi et al. (1993) and Duncan (1996) suggest that the basic claim of this theory—attention derives from the activation of the same circuits that mediate sensory transformations—could be extended also to the ventral stream. The ventral stream arises from the primary visual cortex and largely projects to the inferior temporal lobe. It enables the visual system to categorize visual inputs as visual objects, regardless of the visual conditions in which objects are presented. The computations carried out in the ventral stream produce perceptual and cognitive representations of the visual characteristics of objects and their significance. Chelazzi et al. (1993) recorded single neurons from monkey inferotempo-

ral cortex during a nonspatial selection task in which the relevant object was indicated not by its position but by its identity. In the inferotemporal cortex, where cells are selectively responsive to particular objects or their features, responses to the target object were strong and sustained, whereas after an initial discharge, responses to nontarget objects were suppressed. This neural mechanism permits selection of and better responding to a cued target or, in other words, orienting of attention to a particular object without requiring a control system independent of circuits involved in visual pattern analysis.

Formulating the claims of the premotor theory of attention in more general terms, orienting of attention implies an activation of basic sensorimotor circuits according to the action goal. Attention results, therefore, from an internal representation of the required response during the interval between cue presentation and target presentation. In the dorsal stream, attention is the final outcome of the processing performed in the sensorimotor circuits for eye movements, arm-reaching movements or grasping movements, and possibly other types of action. In the ventral stream, attention results from the activation of the cued object representation. The required response in a visual search task is to detect the cued object, and the enhanced activity of the cells responsive to the target is a way to anticipate this result.

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