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Differential effects of cast shadows on perception and action

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Abstract. In two experiments we investigated the effects of cast shadows on different real-life tasks. In experiment 1, participants were required to make a speeded verbal identification of the target object (perceptual task), whereas in experiment 2 participants were required to reach for and grasp the target object (motor task). In both experiments real three-dimensional (3-D) objects were presented, one at a time, either with their own natural cast shadow (congruent condition) or with the cast shadow of a different object (incongruent condition). Shadows were cast either to the left or to the right of the object. We asked whether the features of the shadow (ie whether it is congruent or incongruent with the object, and whether it is cast to the left or to the right of the object) could influence perception and action differently. Results showed that cast shadows did not influence identification of real 3-D objects (experiment 1), but they affected movement kinematics, producing distractor-like interference, particularly on movement trajectory (experiment 2). These findings suggest a task-dependent influence of cast shadows on human performance. In the case of object-oriented actions, cast shadows may represent further affordances of the object, and as such compete for the control of the action.

1 Introduction

Although shadows are extremely common in everyday-life visual scenes, their effect on human performance has been addressed systematically only in recent years (for a review see Mamassian et al 1998). Most of these studies have focused on the role of shadows during perceptual tasks, and there is now converging evidence that shadows can provide valuable information in tasks where the *spatial* relationships between objects in a scene, or between parts of the same object, have to be taken into account in order to determine the three-dimensional (3-D) layout of a visual scene (see, for example, Kersten et al 1996, 1997; Allen 1999; Madison et al 2001). For instance, Allen (1999) showed that shadows contribute to the correct estimation of object distance. More strikingly, Kersten and colleagues (1996, 1997) showed that motion in depth of an object is perceived dramatically differently depending on the motion of its cast shadow.

However, the issue of whether the presence of shadows can influence people's performance on more complex perceptual tasks such as object recognition remains unclear. Braje and colleagues (2000) explored the effect of cast and attached shadows on recognition of natural objects such as fruits and vegetables. Subjects were required to identify photographs of the stimuli, which could be presented with or without shadows. Results showed that performance (measured both as reaction time and accuracy) was not affected by the presence of shadows. Similar results were found in a face-recognition task. Braje (2003) showed that, in contrast to earlier findings (Braje et al 1998), participants' response times and sensitivity were the same when they had to identify faces in a sequential-matching paradigm, irrespective of the presence or absence of cast shadows. However, different results were also found. In a sequential-matching task, in which participants were required to judge whether two sequentially presented images represented the same object or not, overall performance was slower and less sensitive when cast shadows were absent than when they were present (Tarr et al 1998). Moreover, Castiello (2001) found that the effects of cast-shadow presence or absence can also depend on the congruence between the shadow and the object casting it. Specifically, participants took longer to identify geometrical shapes and familiar objects when presented with an incongruent shadow (ie a shadow that would be cast by a different object) than when presented with a congruent shadow (ie a shadow cast by the object itself). Interestingly, they did not take longer to identify the objects presented with an incongruent shadow than those presented with no shadow. Thus, while shadow presence or absence per se seems to have little (Castiello 2001) or no (Braje et al 2000; Braje 2003) effect when observers have to identify familiar objects, such as geometrical shapes or faces, they appear to play a role for identification of unfamiliar objects (Tarr et al 1998). In addition, if the manipulated feature is the congruence between the shape of the object and the shape of the cast shadow (Castiello 2001), identification is faster when the shadow is congruent with the object than when it is incongruent.

Human performance, however, is not limited to the perceptual domain. Another important behaviour is represented by object-oriented actions such as reach-to-grasp. When one is reaching for an object, features such as its position within the environment, its shape, its size, or the presence of affordances (ie some direct link between the perceived visual properties of an object and an action that may be performed with it—Humphreys 2001), must be taken into account by the visuomotor system in order to programme and execute an adequate motor output. What effects could shadows have on such a motor performance? To date, this issue has remained unexplored. Nevertheless, it is plausible to hypothesise that the motor system needs to take into account any source of information about the 3-D configuration of the object and the 3-D layout of the scene. As discussed above, shadows can provide such information (see, for example, Kersten et al 1996; Allen 1999). Thus, one would expect that a systematic manipulation of the shadow cast by an object could influence performance in a motor task. In the present study we addressed this issue by asking participants to reach and grasp for a real 3-D object presented with a cast shadow. It should be noted that, despite their ecological validity, 3-D objects have never been used as targets to investigate the role played by shadows on human performance. In fact, in all previous investigations of the effects of shadows on perceptual tasks the visual stimuli were 2-D images presented on a computer screen (Kersten et al 1996; Allen 1999; Braje et al 2000; Castiello 2001; Braje 2003). Thus, in addition to possible effects on the motor performance, we first examined whether the manipulation of cast shadows could influence the identification of 3-D objects. This would also allow a more direct comparison between performance in the motor and in the perceptual tasks.

In this study, the question of interest was whether the shadow congruence or its side with respect to the object can influence perception and action differently. Real 3-D objects served as stimuli to test participants in two different real-life tasks. In the first, perceptual, task (experiment 1), participants were asked for a speeded identification of a familiar 3-D object, whereas in the second, motor, task (experiment 2), they were required to reach and grasp it. In both experiments, 3-D objects were presented one at a time either with their own natural shadow (congruent condition) or with the cast shadow of a different object (incongruent condition). The shadow could also be cast either to the left or to the right of the object. The manipulation of shadow position with respect to the object was crucial mainly for the motor task. Cast shadows not only have a shape, they also occupy a position in space. We wanted to examine the effect of these different features of the shadow (ie its shape and its position) on the grasping action. If the shadow acted as a distractor, then its position relative to the target object and the grasping hand would be crucial in defining the features of the resulting interference.

It should be noted that the present study did not include a condition with no cast shadow. On the one hand, results from previous works (see Braje et al 2000; Braje 2003) suggest that the presence/absence of shadows may not be crucial for the identification performance. More importantly, however, we were interested in assessing performance in an experimental setting that was as ecological as we could possibly design. In everyday life, objects hardly ever appear without any kind of shadows, and we did not want to include an experimental condition that could appear somehow 'unreal' (see Castiello 2001) and possibly bias the participants' cognitive set.

2 Experiment 1

2.1 *Methods*

2.1.1 *Participants.* Eight students (two male, six female, aged 19 – 33 years) at Royal Holloway University of London gave their informed consent to participate in the experiment. All participants were right-handed, had normal or corrected-to-normal vision, and were naïve to the purpose of the experiment.

2.1.2 *Apparatus and materials.* The experimental setup consisted of a small bench (30 cm high × 30 cm deep × 50 cm wide) with a translucent top, mounted on a table (see figure 1). Participants sat at the table, on an adjustable chair regulated to bring the participant's chest to the level of the translucent top. Head movements were restrained by means of a chin-rest.

Experimental stimuli were positioned one at a time on the translucent surface, along the participant's body midline, approximately 40 cm from the participant's chest (about 50 cm from the eyes). Stimuli consisted of 10 everyday-life objects of similar

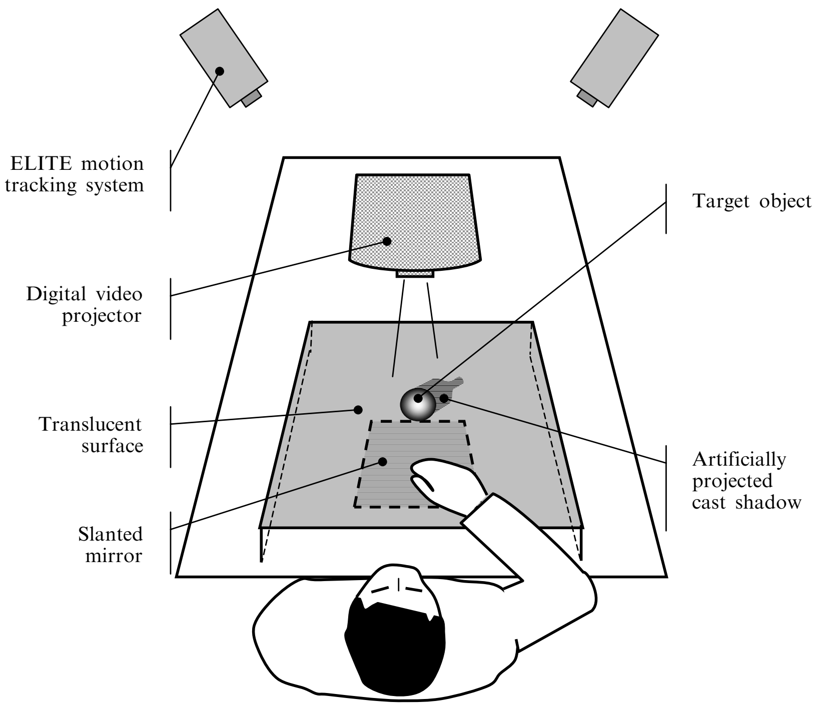
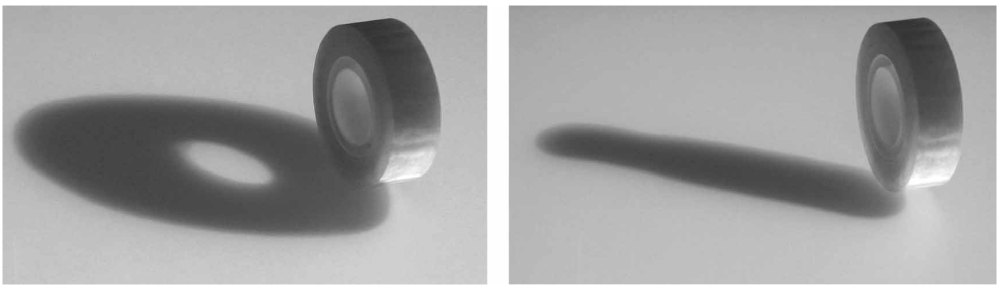


Figure 1. Schematic drawing of the experimental setup used in this study. Please note that the participant's posture and the presence of the ELITE motion tracking system refer only to the motor task required in experiment 2.

size: plug adaptor, roll of clear sticky tape, small bottle of liquid corrector (Tippex$^{\text{TM}}$), sample-bottle, tennis ball, screwdriver, miniature stapler, matchbox, computer mouse, and toy jug. The largest object was the computer mouse (6.5 cm $\times$ 11 cm $\times$ 3 cm), the smallest object was the matchbox (3.5 cm $\times$ 5 cm $\times$ 1.5 cm). Artificial cast shadows were projected from underneath the bench onto the translucent surface with a digital projector and a slanted mirror. This experimental setup resulted in a condition of diffuse ambient illumination from above, plus a strong light source illuminating the object from below. Any shadow that the object could cast on the translucent surface because of the diffuse lighting was annulled by the strong light coming from the projector. Artificial shadows were digitised photographs of the shadow naturally cast by each of the objects under lateral lighting conditions (256-bit grayscale shadow images on a white background, 1102 pixels horizontally $\times$ 630 pixels vertically).

All projected shadows were adjacent to the base of the object, either on its left or on its right side. In addition, they were either the actual cast shadow of the target object (congruent condition) or the cast shadow of a different object in the set of stimuli (incongruent condition). To reduce the number of possible object/shadow combinations, in the incongruent condition each object was associated only with two possible incongruent shadows. An example of the stimuli as seen from the participants' perspective is shown in figure 2.



(a) (b)

Figure 2. (a) Example of congruent condition trial, in which the target (a roll of sticky tape) is presented with its own cast shadow. (b) Example of incongruent condition trial, in which the target is presented with the shadow cast by a different object of the stimuli set (the small bottle).

To allow the experimenter to position the target object on the translucent surface out of the participants' sight, participants wore a pair of lightweight liquid-crystal display (LCD) shutter glasses (Plato Technologies Inc.). The lenses of the shutter glasses were usually opaque, and cleared only during target presentation. The time required for the lenses to change from opaque to clear was approximately 1 ms.

Vocal reaction times (VRTs) for object naming were measured as the time between LCD shutter glasses clearing and response emission, and were recorded by means of a head-mounted microphone. Object identification accuracy was compiled by the experimenter. The digital projector, the LCD shutter glasses, and the microphone were connected to a personal computer and interfaced through a custom-made software that controlled stimulus presentation time and VRT recording.

2.1.3 *Procedure and design.* On each trial, the sequence of events was as follows. While the LCD shutter glasses remained in their opaque state, the experimenter placed the designated target object on the bench top and displayed the relevant shadow on the translucent surface. This resulted in a visual scene which included both the target object and its designated shadow. At this point, a key-press by the experimenter cleared the shutter glasses, allowing full vision of the scene until the participant responded.

The participants' task was to name the target object as quickly and accurately as possible as soon as the lenses cleared. No mention was made with regard to the presence or the type of shadows (congruent, incongruent), so as to investigate whether shadow processing occurred without explicit instructions.

To make sure participants knew the objects they were to recognise, before administering the experimental conditions each of the 10 objects was shown individually, in the exact position and with the exact orientation it would have in the experimental trials. Participants were asked to name each object, and required to stick to that name to identify the stimulus throughout the experimental session.

The experiment comprised a total of 120 trials in quasi-random order, with the exception that, following an incongruent trial, the object to be identified could not be the object corresponding to the previously presented incongruent shadow. Participants were tested in one experimental session of approximately 1 h, divided into two blocks separated by a 5 min interval. A minimum of 10 practice trials was performed before the experiment; these were discarded from subsequent analyses.

2.2 *Results and discussion*

VRTs faster than 150 ms or slower than 2000 ms, as well as trials in which participants identified the object incorrectly, were excluded from further analysis. Errors (ie outliers and incorrect identifications) accounted for less than 7% of the trials, equally distributed among the experimental conditions ($F < 1.1$, ns).

VRTs for the remaining trials were entered into a two-way analysis of variance (ANOVA), with shadow type (congruent or incongruent) and shadow side (left or right) as within-participants factors. None of the factors in this analysis reached significance (main effect of shadow type: $F_{1,7} = 1.2$, ns, 591 versus 604 ms; main effect of shadow side: $F_{1,7} = 0.3$, ns, 596 versus 599 ms; interaction shadow type $\times$ shadow side: $F_{1,7} = 1.4$, ns). In contrast to previous studies (Tarr et al 1998; Castiello 2001), these findings suggest that cast shadows (at least the ones used in our experimental setup) may have little effects during object-recognition tasks.

Two factors may account for the results. First, the task may have been too easy. In particular, the unlimited target exposure time together with the absence of visual masking might have cancelled any influence of shadows on the identification performance. This possibility is discussed in more detail in section 4.

Another possible reason for the difference between the present and previous studies may lie in the fact that in our work real 3-D objects, rather than 2-D images of natural objects on a computer screen, were presented. But why should object dimensionality play a role in shadow processing? It can be suggested that, when dealing with real everyday-life 3-D objects, the perceptual system might not need to take into account cast shadows, if they are irrelevant for the identification task. In other words, the 3-D objects in the present study might be so salient that, when participants have to identify them, shadows are not taken into account. However, the processing weight of cast shadows can be different in a different experimental paradigm, and this can explain the discrepancy between the present findings and previous work. For example, when the perceptual task implies recognition of whether two images represent the same 2-D unfamiliar object or not (as in the sequential-matching paradigm used in Tarr et al 1998), shadows provide crucial cues for task performance, possibly by making the spatial relationship between object parts more salient. In the recognition task used by Castiello (2001), instead, it can be argued that the rendering of the objects (2-D geometrical shapes and natural objects) necessary to create the experimental stimuli resulted in cast shadows unnaturally salient, thus causing them to compete with the object for processing resources more than is usually the case with natural objects.

Both factors—the use of 3-D objects and allowing unlimited target exposure—were functional to experimental 2, which was designed to examine the influence of cast shadows on object-oriented actions.

3 Experiment 2

3-D objects carry a stronger functional (motor) significance. This in turn shifts the weight of processing from a purely perceptual analysis to a motoric analysis that considers possible actions that the object affords. By following this line of reasoning it could be hypothesised that information conveyed by the shadow cast by 3-D objects may have a greater impact on the programming and execution of an overt action than on a purely perceptual judgment. In experiment 2 we tested whether the presence of shadows has an effect on object-oriented actions such as reaching-to-grasp. In particular, the hypothesis we wanted to examine was whether shadow incongruence or shadow side produced any interference-like effect on the movement.

3.1 *Methods*

3.1.1 *Participants.* Eight students (three male, five female, aged 19 – 30 years) at Royal Holloway University of London took part in experiment 2. All participants were right-handed, had normal or corrected-to-normal vision, and ignored the purpose of the experiment. None had taken part in experiment 1.

3.1.2 *Apparatus, materials, procedure, and design.* Apparatus, materials, procedure, and design were the same as for experiment 1, with the following exceptions. Three reflective passive markers (3 mm diameter) were attached to the participant's right wrist (on the radial aspect of the distal styloid process of the radius), index finger (on the radial side of the nail), and thumb (on the ulnar side of the nail). Movements were recorded with the ELITE system (Ferrigno and Pedotti 1985) by means of four infrared cameras (sampling rate 100 Hz). The calibrated working surface was a parallelepiped (60 cm long, 30 cm wide, 60 cm high) from which the spatial error measured from stationary and moving stimuli was 0.4 mm.

The right arm, dominant for all participants, rested on the translucent surface of the bench. The hand starting position was on the participant's sagittal axis, 30 cm from the target object. In this position, the shoulder and the elbow were flexed about $5° – 10°$, the forearm was semipronated, and the wrist was in $10° – 15°$ of extension. The index finger and the thumb were held gently opposed. Participants were instructed to perform a reach-to-grasp movement to the target object at their leisure as soon as the LCD shutter glasses lenses cleared. No emphasis was put on the speed of action, mainly for two reasons. First, we were interested in naturalistic movements, so no emphasis was put on movement speed. Speeded movements can result in altered kinematics (Wing et al 1986), which may confound the interpretation of any difference we may obtain between the experimental conditions. Second, if movement speed were stressed, participants may have unconsciously adopted the strategy of releasing the starting switch as soon as the LCD shutter glasses cleared, without completion of movement programming. If this were the case, and given the repetitive nature of the task (movements were always directed towards the same spatial position) we feel this is not unlikely, then movement reaction times would not be an informative measure of shadow interference [see also Meegan and Tipper (1998) for a similar argument].

3.2 *Results and discussion*

Data from each movement acquisition were filtered with a FIR linear filter with a transition band of 1 Hz (sharpening variable 2—D'Amico and Ferrigno 1992).

The dependent variables of interest for the present study were the kinematic parameters known to be sensitive to contextual interference effects (see, for example, Tipper et al 1992; Bonfiglioli and Castiello 1998). These kinematic parameters were extracted for each movement and included: (a) movement duration (the time taken from the beginning of the reaching action to the time when the fingers closed on the target and there were no further changes in the distance between the index finger and thumb); (b) percentage deceleration time (the time between wrist peak velocity and movement end, expressed as a percentage of total movement duration); (c) amplitude of maximum grip aperture (the maximum opening of thumb and index finger); (d) percentage time of maximum grip aperture (at which point during movement execution maximum grip aperture occurred, expressed as a percentage of total movement duration); and (e) wrist trajectory in 3-D space.

Mean movement duration for each participant was entered into a two-way ANOVA, with shadow type (congruent or incongruent) and shadow side (left or right) as within-participants factors. This analysis did not reveal any significant main effect or interaction (all Fs < 1.2), suggesting that participants took comparable time to grasp the object, irrespective of whether the shadow was congruent or incongruent (1427 versus 1437 ms) and regardless of whether it appeared on the left or right of the object (1420 versus 1440 ms). By contrast, a similar ANOVA on mean deceleration time showed a significant main effect of shadow side ($F_{1,7} = 6.7$, $p < 0.04$), caused by longer deceleration times when the shadow was cast to the left of the object than to its right (52.2% versus 51.5%, respectively). No other significant main effect or interaction emerged (all Fs > 1).

Mean values for maximum grip aperture and percentage time of maximum grip aperture were analysed with the same ANOVA as before. Analysis of percentage time of maximum grip aperture did not reveal any significant main effect or interaction (all Fs < 1.6). Similar results were found for the analysis of the amplitude of maximum grip aperture, although the main effect of shadow side approached significance ($F_{1,7} < 4.6$, $p = 0.07$). In particular, a larger grip aperture was obtained when the shadow was cast to the left than when it was cast to the right of the object (55.6 versus 54.8 mm). Taken together, these results suggest that shadow type and side had little effect on the pattern of the manipulation component.

To examine whether shadow type and side influenced wrist trajectory in 3-D space (ie the movement spatial path), we analysed the deviation of wrist trajectories from an imaginary reference line connecting the start-position and the end-position of the movement. This is a standard method to express the curvature of wrist trajectory in 3-D space as a single parameter (eg Haggard and Richardson 1996). In the present study, this reference line was calculated for each participant separately, to obtain a measure of trajectory deviation independent of any inter-participant differences in hand positioning. Specifically, the reference line was computed for each participant as the line connecting the average mid-point between thumb and index finger at movement onset, with the average mid-point between thumb and index finger at movement end (when fingers closed on the target object). All trajectories fell on the right of the reference line. Deviation of wrist trajectories from this reference line was then computed for points on the trajectory corresponding to the 20%, 40%, 60%, and 80% of total movement time.

Mean deviations for each participant in each experimental condition were then submitted to a repeated-measures ANOVA, with shadow type (congruent or incongruent) shadow side (left or right), and percentage of movement time (20%, 40%, 60%, 80%) as within-participants factors. When necessary, a posteriori analyses were carried out with the Fisher least-significant difference test (Howell 1999).

The analyses revealed a significant main effect of the percentage of movement time ($F_{3,21} = 21.4$, $p < 0.001$), reflecting different distances of wrist trajectories from the reference line at various stages of the movement. Maximum trajectory deviation occurred at 40% of total movement time ($p < 0.002$ on all protected paired t-tests).

This result is in agreement with previous studies, where it was found that maximum lateral trajectory deviation occurs during mid-reach (Jackson et al 1995).

More important for the present study was the significant interaction between shadow type and the percentage of movement time ($F_{3,21} = 6.07$, $p < 0.004$). A posteriori comparisons revealed that early on during the movement (at 20% of movement duration) wrist trajectory deviated more for incongruent than for congruent cast shadows (60.9 versus 58.8 mm, $p < 0.02$). By contrast, at the final stage of the movement (at 80% of movement duration) this pattern was reversed, with larger deviations for congruent than incongruent shadows (39.3 versus 36.8 mm, $p < 0.01$). Plots for this interaction are presented in figure 3c, together with the actual wrist mean trajectories as seen from above (ie left/right – front/back plane) for congruent and incongruent trials (figure 3a). Finally, there was a significant interaction between shadow side and the percentage of movement time ($F_{3,21} = 4.62$, $p < 0.0124$). A posteriori analysis revealed that movement

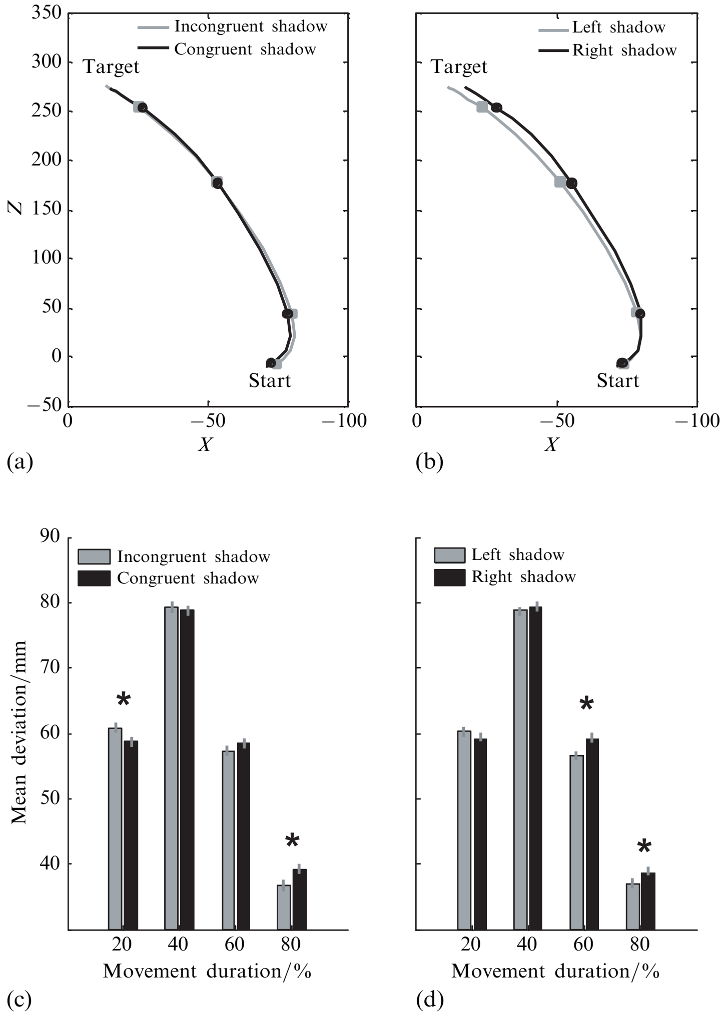


Figure 3. (a) and (c): Mean wrist trajectory deviation as a function of shadow type and the percentage of movement time. (b) and (d): Mean wrist trajectory deviation as a function of shadow side and the percentage of movement time. (a) and (b) show an overhead view of wrist trajectories in the $X-Z$ (left/right – front/back) plane. Please note that this graph does not take into account trajectory displacements along the Y (up/down) axis. (c) and (d) show the plots of mean deviation of trajectories from the reference line. Bars indicate 95% confidence intervals.

trajectories deviated more when the shadow was cast to the right than when it was cast to the left of the object, both at 60% of movement duration (56.7 versus 59.3 mm, $p < 0.03$) and at 80% of movement duration (37.2 versus 38.9 mm, $p < 0.03$). Plots for this interaction are presented in figure 3d, together with the actual wrist mean trajectories as seen from above (ie left/right – front/back plane) for left-shadow and right-shadow trials (figure 3b).

In summary, the results of experiment 2 showed that, unlike in experiment 1, performance in this object-oriented motor task was affected by the features of the shadow cast by the object. The main influence was observed on wrist trajectories, and was related both to the position of the shadow with respect to the object (left or right) and to shadow type (congruent or incongruent).

4 General discussion

We investigated here the effects of cast shadow on two different types of tasks: object identification and object-oriented action (prehension). Results showed that performance on the identification task was not affected by the congruence between the object and the shadow, or by the position of the shadow with respect to the object. By contrast, both these shadow features influenced movement kinematics during the prehension task.

4.1 *Cast shadows and object identification*

Previous researchers who investigated the role of cast shadows in object-recognition tasks manipulated either the presence/absence of cast shadows (eg Braje et al 2000), or the congruence between the shape of the object and the shape of its associated cast shadow (eg Castiello 2001). These studies have not consistently proven whether performance is helped or hindered by shadows, with facilitatory effects being observed in some cases (Tarr et al 1998; Castiello 2001) but not in others (Braje et al 2000; Braje 2003). Thus, it appears that the influence of cast shadows may become apparent depending on specific task demands (eg varying the shadow/object congruence, or using unfamiliar target objects). The findings of experiment 1 support this notion by providing new evidence that the human visual system may not suffer from the interference of cast shadows during recognition of real 3-D objects. One possibility is that the perceptual task was too simple to detect what might be somewhat subtle effects of cast shadows on recognition performance. In particular, it can be argued that unlimited target exposure time and the absence of visual masking may cancel any effects of cast shadows on object recognition. However, it should be noted that, even when shorter target exposure times were adopted, the effects of shadows on object recognition could not be found. Results from Braje et al (2000, their experiment 3) showed that even with an exposure time as short as 30 ms, and even when the visual stimulus was followed by a mask, participants' performance was unaffected by the presence of shadows. Moreover, pilot data from our own laboratory on the specific task and paradigm used for experiment 1 showed that even with shorter target exposure times of 500 and 150 ms, performance on the identification task was not affected by any of the features of the cast shadow. We then reasoned that for an effect to occur in our recognition task we should try to increase, rather than decrease, target exposure time, in order to allow participants more time to become aware of the shadow and, possibly, of its congruence/incongruence with the object casting it.

Another point of caution should be raised in the interpretation of the present findings. In the present study, to obtain a visual input that contained only the target object and the relevant shadow (ie to prevent natural cast shadows in the visual scene), target objects were always presented under diffuse lighting conditions, while artificial cast shadows were projected near the target object from underneath the translucent surface on which the object was resting. This specific setup inevitably produced an unusual visual scene, in which cast shadow always appeared in the absence of any attached shadow (see Mamassian et al 1998). This may have introduced an additional element of incongruence within the scene, which could have in turn obliterated any possible subtle effect of object/cast shadow incongruence on identification latencies. This explanation would also be supported by the results of a previous study by Castiello (2001), who reported that object recognition is hindered when cast and attached shadows convey contradictory information about the direction of lighting.

4.2 *Cast shadows and object-oriented actions*

While performance on the object-identification task was unaffected by cast shadows, a substantially different pattern of results emerged from the analyses of reach-to-grasp movements.

Movement duration was not affected by the features of the shadow; however, there was an increase in the proportion of deceleration time (ie the time spent after peak velocity) when shadows were cast to the left of the object than when they were cast to the right. Previous studies have demonstrated that deceleration time is longer during reaches with a higher index of difficulty (for example, towards target objects in the presence of a distractor, or towards smaller target objects), than when the index of difficulty is lower (for example, Jackson et al 1995; Elliott et al 1999). If the increase in deceleration time is taken as an indication that the visual scene contains an interfering element, then the longer deceleration time observed when the shadow was cast to the left of the object provides initial evidence that cast shadows may represent a potential 'distractor' for the motor system. Although, strictly speaking, the cast shadow cannot be considered a 'distractor', as it could never become the target of the action, nor did it actively compete for attentional resources (see Bonfiglioli and Castiello 1998), it can nonetheless be argued that the mere presence of a non-target object within the visual scene (ie the shadow) may have attracted the participants' attention, possibly interfering with the ongoing action. Accordingly, the longer deceleration time observed in the left-shadow condition may indicate that left shadows captured participants' attention to a greater extent than right shadows. The specificity of this effect for left shadows only may reflect the fact that at the final stage of movement execution right shadows were partially occluded from view by the right hand approaching the target object.

Further evidence in favour of the notion that cast shadows interfered with the motor performance comes from the analyses of wrist trajectories. Wrist trajectories in the second half of the movement differed as a function of whether the shadow was cast to the left or to the right of the object. In the absence of a neutral condition, with movements performed towards an object with a non-lateralised cast shadow, we can only speculate on the basis of the relative position of the two trajectories with respect to each other. In particular, when the shadow was cast to the right, wrist trajectory deviated more towards the right, whereas when the shadow was cast to the left, the trajectory deviated more towards the left. In other words, when reaching for an object in the presence of a distracting cast shadow, systematic deviations of wrist trajectories strikingly reflected the spatial layout of cast shadows with respect to the object.

When programming an action, the visuomotor system must take into account not only the target object, but also any other distractor within the visual scene. Such distractors might 'capture' the participants' attention and produce interference effects on movement planning by competing with the target for motor response. It has been suggested that the amount of competition reflects the relative salience of distractors (Houghton and Tipper 1994). This, in turn, determines the level of inhibition required to prevent execution of responses associated with each distractor and which effects each distractor will have on target-oriented movements (Tipper et al 1997; Meegan and

Tipper 1998). A point that is particularly relevant to the present study is that hand trajectories during object-oriented actions appear to be particularly sensitive to non-target salience. When the distractor is salient, hand trajectory veers away from it (Tipper et al 1997). On the contrary, when the distractor is *not* salient, hand trajectory veers towards it (Tipper et al 1997; Welsh et al 1999; Chieffi et al 2001)

In the present study, the salience of the cast shadow was very likely to be low. It did not constitute a physical obstacle to the movement, it was not located on the movement path (being projected away from participants), and it could never become a potential target. Moreover, a shadow is a bidimensional 'object', and as such it does not have any graspable attribute. For these reasons, it is unlikely that the shadow competed strongly with the target object for the control of the reach-to-grasp movement that participants were asked to perform (Castiello 1998). Nonetheless, it appears that the cast shadow could not be completely discarded. The results of experiment 2 are thus consistent with the findings previously described in the literature in showing that a low-salience competing object (here, a cast shadow) shifted the hand trajectory towards the distractor, rather than away from it. One possibility is that processing of shadow position interfered with processing of target position, hence the distractor-like effects on wrist trajectories.

Another important point to note refers to the little effect of cast shadows on the manipulation component of the movement. It is now well-established that both the reaching and the manipulation components are affected by the extrinsic (for example, position or orientation) and the intrinsic (for example, size, shape, or volumetric properties) features of the target object during object-oriented actions (Gentilucci et al 1991; Jakobson and Goodale 1992; Desmurget et al 1996). Cast shadows can be informative as to both extrinsic and intrinsic features of an object. In this study, the information regarding the intrinsic features of the target provided by the target itself was put in potential conflict with the information on the intrinsic features of the target provided by the incongruent shadow. The fact that the manipulation component was unaffected by such conflicting information suggests that, during the selection process of an action such as the reach-to-grasp studied here, the motor system takes into account 'graspability', which is an attribute not provided by cast shadows or 2-D shapes (Culham 2004).

Westwood et al (2002) recently examined manual prehension of 2-D and 3-D objects. One interesting aspect of the study was the comparison between grasping of shadowless images and grasping of images with shadows (the so-called 2-D enhanced stimuli). Normal participants adopted a different pattern of finger aperture when grasping 2-D and 2-D-enhanced stimuli, compared to 3-D stimuli. This suggests that participants may adopt an unnatural grasping movement when asked to grasp a 2-D image. Instead, they may 'pantomime' the grasping movement by reaching out towards the image and shaping their fingers as if they were to match the perceived size of the target.

This notion has now found further support from a study by Culham (2004), who found that the cortical system normally activated during object-oriented actions is not activated by 2-D stimuli. Similar results were obtained by Castiello (1998) in a study on reaches towards 3-D stimuli while attention was diverted towards distracting information consisting of either 2-D projected shapes or 3-D objects. When the distractor was 3-D, both the reaching and the grasping components were altered. Instead, when it was 2-D, only the reaching component (that deals with the extrinsic features of an object) was modified, whereas the grasping component (that deals with the intrinsic features of the object) was not altered. Thus, it can be suggested that the distractor dimensions (2-D or 3-D) selectively influence the reach or the grasp component of a prehension movement. Unfortunately, neither Westwood et al (2002) nor Castiello

(1998) investigated the 'shadow' issue directly, which makes it hard to reconcile their findings with results from the present study. However, both studies suggest that shadowless 2-D objects and distractor do not provide access to a 3-D object representation, which in turn activates neural circuit related to grasping actions. In addition, the absence of interaction between shadow type and shadow side in the present study may represent further evidence in this direction. In theory, the presence of an incongruent shadow could capture attention to a greater extent than the presence of a congruent shadow. However, this can be expected only if the intrinsic features (ie the shape) of the shadow have been processed. The results of Castiello (1998) reported above suggest that only the *extrinsic* features of a 2-D distractor are processed by the motor system, as evidenced by the selective interference found in the reaching but not in the grasping component of the action.

Finally, although in the analysis of the amplitude of maximum grip aperture the main effect of shadow side was only approaching significance ($p = 0.07$), it is interesting to observe that such amplitude was wider when participants had to grasp the target object in the presence of a left shadow than that of a right shadow. As demonstrated by Jackson et al (1995), maximum grip aperture is significantly larger when participants reach for targets in the presence of distractor objects. Therefore, this finding, together with the longer deceleration time found for left cast shadows, provides converging evidence that, in our experimental setup, left cast shadows represented a visual distractor to a greater extent than right cast shadows.

5 Conclusions

The present study has demonstrated that cast shadows can have differential effects on human performance. The implication here is that 3-D objects and their associated shadows may engage the motor system, but not the perceptual system, in an obligatory manner. We think the key difference between the perceptual and motor tasks has mainly to do with different task demands, which reflect both what sort of response is required and which information is relevant to accomplish it. Performing a grasping task requires the processing of a specific set of information, including the spatial layout of the scene and other object features useful to programme and execute the correct motor output. In this perspective, the differences we found in the present study between the perceptual and motor tasks may well depend on the fact that visual information is relevant in the recognition task only *before* the response is emitted, whereas in the motor task visual information can be used also *during* movement execution as it can be relevant for online movement control. This point is supported by the fact that interference was mainly found in two kinematic parameters, namely deceleration time and wrist trajectory, which are particularly sensitive to visual feedback during movement execution.

A possible reason for the differential effects on the perceptual and the motor performance is that the visual system has evolved in order to be able to recognise objects irrespective of the features of their variable, unstable, cast shadows, and for this reason is immune to them. In contrast, shadows are potentially informative as to the spatial layout of the scene. For this reason, the motor system cannot discount them, as they may be useful during action planning and execution.

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