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Research report

Dividing attention between form and motion during transparent surface perception

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Abstract

Attending to objects implies the concurrent process of features that are analyzed in different visual subsystems or domains. Previous works have shown that attention cannot be simultaneously directed to the components of motion present in two transparent surfaces [M. Valdés et al., Cognition 66 (1998) B13–B23], even though they occupy overlapping regions of space. In this paper, possible across-domain effects in object-based attention were examined using a conjunction of form and motion in transparent superimposed surfaces. After directing attention to one surface, different combinations of motion and form judgements were performed. If both attributes belonged to the same surface, no interference was found. If the two judgements concerned features from different surfaces, a large performance cost was present for the attribute belonging to the uncued surface. The fact that these effects cut across feature domains supports the integrated competition hypothesis [J. Duncan, Attention and Performance XVI, The MIT Press, 1996, pp. 549–578].

Theme: Sensory systems

Topic: Visual psychophysics and behavior

Keywords: Visual attention; Object; Transparent surface; Motion; Form; Human psychophysics

1. Introduction

Previous work has shown that judging two attributes concerning one object can be performed as accurately as judging only one attribute; in contrast, interference arises when two attributes of different objects are discriminated [10,13,28]. In these studies, small superimposed objects were used in an attempt to preclude the use of spatial selection. The two-object cost therefore was explained by invoking object-based mechanisms. However, this conclusion has been criticized because the two superimposed stimuli could have differed in spatial extent or in spatial frequency content, which would offer an alternative basis for selection other than the segmentation of the scene into objects [14,21,30].

To control for these competing interpretations, Valdés-Sosa et al. [24,25] used superimposed transparent surfaces defined by the relative motion of random dots in a series of experiments. Each surface can be considered as an ‘object’ in a very elementary sense (a numerable ‘thing’, see [32]). They form two perceptual groups built on the basis of Gestalt principles such as similarity and common fate [20] (see [26] for a review). The advantage of using transparent motion is that both surfaces can occupy the same region of visual space. The two surfaces can also be carefully matched in spatial frequency content. Under these conditions, two brief events on one surface were discriminated without interference, whereas attention to one surface impaired judgments about events on the other surface. These results are not easily explained by selection based on simple sensory filters, and are consistent with object-based attention (for more details see [23,25]).

Despite offering a tighter control over several variables, these experiments are limited because they were restricted to the use of motion-discrimination tasks. Other authors have explored the cost of dividing attention between different perceptual objects using other attribute conjunc-

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tions such as color, form, texture, orientation, spatial frequency [2–4,29]. However, all these features are processed within the same visual pathway, the ventral pathway [11], and it could be argued that these results, as in Valdés-Sosa's experiments [24,25], reflect some sort of idiosyncratic interference between signals within the same processing module or visual subsystem. This is an important issue, since most models that predict object-based limitations in attention are not restricted to single-feature domains. In fact the recently stated 'integrated competition hypothesis' [5], (see also [27]) posits that attending to one attribute of an object will lead to enhancement of its other attributes and to inhibition of all features of competing objects. These processes would extend to the multiple and widespread brain modules where those attributes are represented. The only psychophysical study we are aware of that has used conjunctions of attributes coming from different domains was carried out by Duncan and Nimmo-Smith [6]. In their study they reported interference between motion direction and texture judgments but the use of spatially separate sets of stimuli hampers conclusions about object-based processes.

In the present study, the possibility of across-domain effects in object-based attention was examined with the transparent motion paradigm developed in our group to preclude spatial selection. We studied the division of attention between transparent superimposed surfaces defined by small moving elements that could vary in shape. Required discriminations could involve both motion and non-motion attributes. The following questions were formulated: would a 'two-surface' cost be obtained for conjunctions of motion and non-motion attribute judgements, as in the previous studies? Further, would the 'two-surface' cost arise if pairs of non-motion attributes were used?

2. Material and methods

Eight university graduates (six males) participated in three experiments as volunteers. All the subjects had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. Ages ranged between 23 and 34 years. Due to the difficulty of the task, potential subjects first practiced and were replaced if accurate performance (above 75% correct responses) was not obtained.

The stimuli consisted of a set of 100 small circles interspersed with a set of 100 small squares (see Fig. 1). In Experiment 1, both sets were colored white. In Experiments 2 and 3, the circles were colored red and the squares were colored green. The background was always black. The squares and circles were about 5 pixels in diameter (about 9 arcmin). In Experiments 2 and 3, heterochromatic flicker photometry was employed for each subject to obtain equiluminant red and green colors (for more details see [23–25]). All these figures were drawn within an imaginary circle with a diameter of 6 degrees centered on a fixation point (FP) of 0.15 degrees.

Each trial started with a baseline in which the circles rotated rigidly around the FP in clockwise direction, whereas the squares rotated counter-clockwise. The speed of rotation was 40 degrees/s. This baseline was perceived as two semitransparent surfaces moving in the same area of visual space. After 1500 ms both sets were simultaneously and linearly displaced for a period of 1000 ms, each moving in a different and randomly chosen direction, at a speed of about 4 degrees/s. If an element passed the border of the imaginary circle surrounding the FP, it was wrapped around to an opposite but symmetrical position on the circle.

Eight directions of rectilinear motion were used, starting

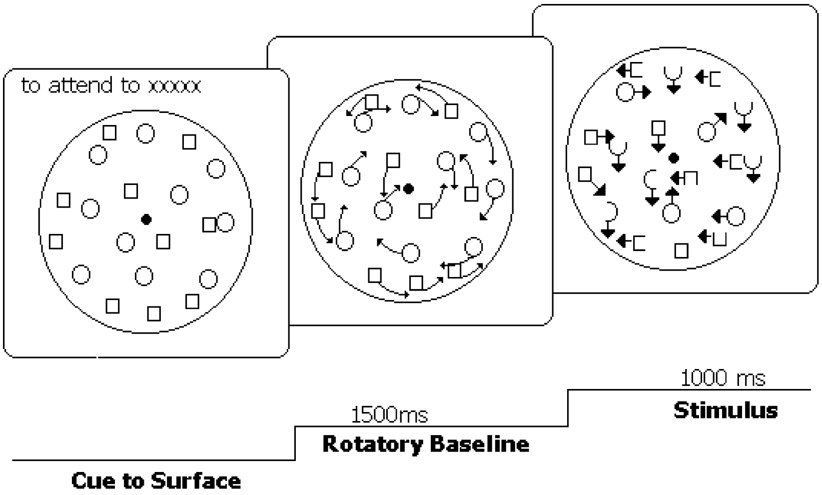

Fig. 1. Stimulus configuration and timing. At the beginning of each trial, subjects were asked to prioritize attention to circles or squares. After fixating the FP, participants initiated each trial by pressing the spaced bar of the computer keyboard. Trials started with a baseline in which circles rotated rigidly around the FP in clockwise direction, whereas squares rotated counter-clockwise during 1500 ms. After rotation, each set were simultaneously, and linearly displaced for a period of 1000 ms.

at 0 degrees and with 45 degree steps. The displacements were partially coherent within each set, with 60 of 100 elements moving in the same direction and the rest of the elements moving randomly in any of the other seven directions. At the same time and during the linear displacement, 80% of the coherently moving elements became semicircles or open squares with the gap oriented to one of the four cardinal positions (see Fig. 1). The gap of the other 20% was randomly oriented to the three positions not employed by the coherent oriented subset. Partially coherent motion and partially coherent form changes were used to compel attention to the complete ensemble instead of a focus on individual elements and the participants were warned that direction and orientation judgements based on individual dots could be misleading.

In the three experiments on each trial the subjects had to discriminate the dominant tendency of two attributes. The attributes to be judged were the direction of motion of the circles (dc), the direction of motion of the squares (ds), the orientation of the gap in the circles (oc) or the orientation of the gap in the squares (os). Six pairs of attributes were possible for discrimination: ‘dc–oc’, ‘ds–os’, ‘dc–ds’, ‘oc–os’, ‘ds–oc’, ‘dc–os’. Note that the first two pairs (‘dc–oc’ and ‘ds–os’) concerned the same surface but the other pairs concerned different surfaces.

In Experiments 1 and 2, subjects were cued before each trial to which surface they should attend. Therefore they were aware that either the direction of motion or the gap orientation for that set of elements had to be reported first. They did not know which was the second attribute to be reported. However in Experiment 3 the cue at the beginning of the trials instructed them on the specific pair of attributes they had to identify and to which set, circles or squares, they belonged. Thus trials were either ‘same-surface’, when the two judgements concerned the same surface, or ‘two-surface’, when the judgements concerned different surfaces in all experiments. Pair of attributes and type of trial were always presented in a random order.

Experiments were comprised of two blocks of 150 trials each and were performed on different days. The order in which Experiments 1 and 2 were carried up was counterbalanced over participants. Experiment 3 was in all cases performed last. Experiments took place in a room with dim illumination. After fixating the FP, participants initiated each trial by pressing the space bar of the computer keyboard. Fixation was required until stimulus motion offset. At this point in time subjects were requested to give their answers via the computer keyboard. For the two first experiments only in this moment were they informed which attribute had to be reported for the cued surface (first response), and which surface and attribute concerned the second judgment (second response). Note that the only information supplied before the trials in Experiments 1 and 2 was about which surface and which attribute was to be reported first. Incorrect responses were signaled by a 500 ms beep on the computer loudspeaker.

Percent-correct scores were adjusted to compensate for guessing [17]. Orientation judgments were corrected for a 0.25 guessing-level, while direction judgements were corrected for a 0.125 level. The percentage of correct responses (corrected by guessing-level) was submitted to a rm-ANOVA using two factors: response order with two levels (one from first responses and the other from second responses) and type of judgment with six levels (corresponding to all possible combinations of direction and orientation judgments). The Greehouse–Geisser correction was used when necessary to mitigate violations of the sphericity assumption in repeated-measures designs [12] and the corresponding epsilon values are reported. As no significant differences between circles and squares were found in a preliminary data exploration, element shape is ignored in subsequent analysis.

3. Results

3.1. Experiment 1

Fig. 2a shows the proportion of correct responses as a function of response order and type of judgment. Very clear patterns emerged. A significant effect of response order was observed ($F(1,7) = 6.55$, $P < 0.038$), with the first response more accurate than the second. The type of judgment was highly significant ($F(5,35) = 18.5$, $P < 0.0002$, $e = 0.37$). The interaction between response order and type of judgment was also highly significant ($F(3,35) = 38.8$, $P < 0.00001$, $e = 0.46$).

Planned comparisons showed that first responses, irrespective of judgment type, were equivalent. In sharp contrast, there was a great variability among second responses ($F(3,35) = 18.32$, $P < 0.00001$). The accuracy of second responses in ‘same-surface’ trials differed significantly from that of second responses in ‘two-surface’ trials ($F(1,7) = 28{,}3$, $P < 0.0011$). The second response was equivalent in accuracy for the corresponding first response in ‘same-surface’ trials. In contrast, second responses in ‘two-surface’ trials were significantly less accurate than the corresponding first responses ($F(1,7) = 39.2$, $P < 0.0004$).

3.2. Experiment 2

The addition of color introduced little variation (Fig. 2b) in the pattern of effects already described for Experiment 1. However, accuracy was larger for the cued surface and lower for the uncued surfaces when color was used. Therefore the difference between accuracy between the cued and uncued surfaces was significantly larger in this experiment than in Experiment 1 ($F(1,7) = 10.3$, $P < 0.015$).

Again, a strong significant effect of response order was observed ($F(1,7) = 159.4$, $P < 0.00001$), more accurate for

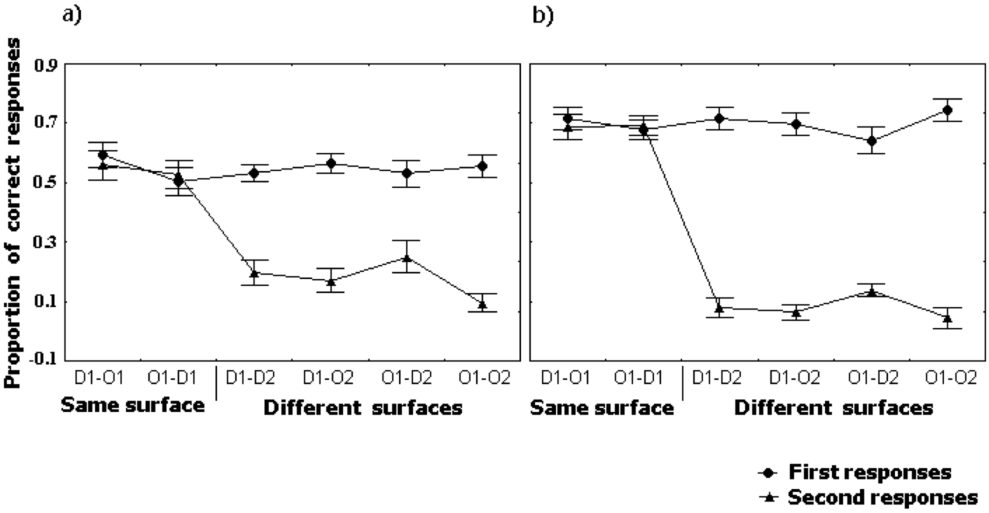

Fig. 2. Mean percentage and standard errors of correct responses as a function of response order and type of judgment in: (a) Experiment 1, (b) Experiment 2. Pairs of judgments presented to participants are shown in the X-axis. The first judgment always concerned a feature (D = motion direction, O = gap orientation) of the cued set (1). The second judgment could concern either the cued (1) or the uncued (2) set. In both experiments, first responses were more accurate than second responses. However accuracy for the second response was equivalent to the accuracy for the first one when they corresponded to a 'same-surface' trial.

the first responses. The type of judgment was highly significant ($F(5,35) = 65.8$, $P < 0.00001$, $e = 0.62$). The interaction between response order and type of judgment as in the previous experiment was highly significant too ($F(3,35) = 133.9$, $P < 0.00001$, $e = 0.56$).

Planned comparisons showed no differences among first responses. As expected, a statistically significant variability is present among second responses ($F(5,35) = 100$, $P < 0.00001$). Second responses did not differ between types of 'same-surface' trials or between types of 'two-surface' trials. However the accuracy of second responses in 'same-surface' trials differed significantly from that of second responses in 'two-surface' trials ($F(1,7) = 332$, $P < 0.00001$). The second response was equivalent in accuracy to the corresponding first response in the 'same-surface' trials. In contrast, second responses in 'two-surface' trials were significantly less accurate than the corresponding first responses ($F(1,7) = 319$, $P < 0.00001$).

3.3. Experiment 3

The results from the previous experiments show an advantage for the processing of single objects as opposed to two objects. In other words, if attention is drawn to one surface its attributes were processed efficiently, whereas judgments about any attribute from the other surface were hampered. However, a different cueing procedure was possible. The attributes to be reported could be cued beforehand. Would the division of attention with this type of cueing be more efficient? Could the subject with sufficient preparation split his attentional resources efficiently between the two surfaces? Would the performance be similar for all four pairs of discriminations in 'two-surface' trials? With these questions in mind we carried out our last experiment.

Warning the subjects on the specific pair of features and their location produced a general pattern of results similar to those obtained in the two previous experiments with some minor but interesting differences (Fig. 3). A strong significant effect of response order was again observed ($F(1,7) = 39.9$, $P < 0.0004$), with more accuracy for the first than the second responses. The type of judgment was also highly significant ($F(5,35) = 31.4$, $P < 0.00001$, $e = 0.55$). As in the previous experiments the interaction between response order and type of judgment was highly significant ($F(3,35) = 19.5$, $P < 0.0002$, $e = 0.34$).

Planned comparisons for each pair of attributes on 'same-surface' trials showed equivalent accuracy for first and second responses. Neither type of discrimination nor its interaction with the response order was significant. In the case of 'two-surface' trials when a pair of attributes concerned the same discrimination (orientation–orientation or direction–direction), there was again a significant difference in the planned comparisons among first and second responses ($F(1,7) = 20.9$, $P < 0.003$). But the type of discrimination and the interaction of it with the response order were not significant. However a very interesting result emerged when the pair of attributes concerned different discriminations (direction–orientation or orientation–direction). Here, the difference among first and second responses was also highly significant ($F(1,7) = 86.9$, $P < 0.00003$). But interestingly the type of discrimination and even more, its interaction with response order

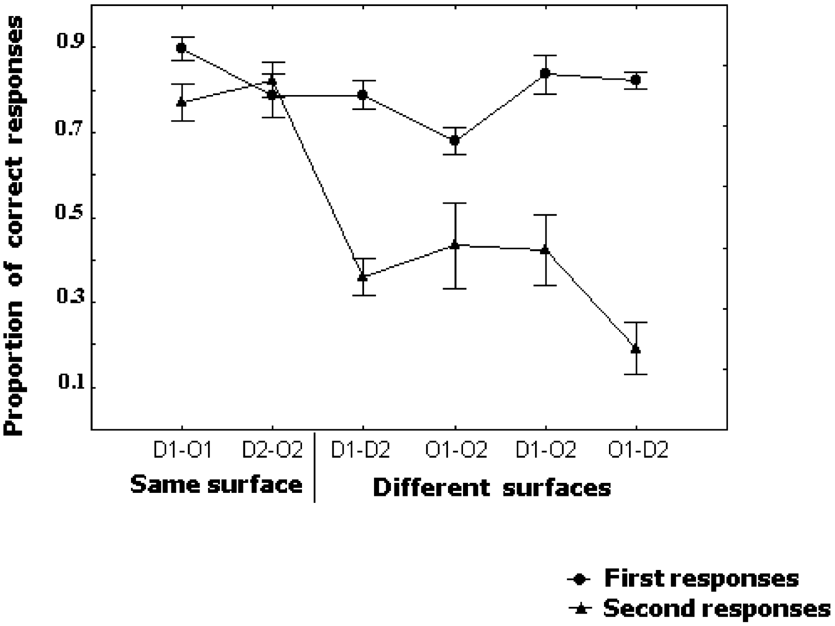

Fig. 3. Mean percentage and standard errors of correct responses as a function of response order and type of judgment in Experiment 3. Pairs of judgments presented to participants are shown in the X-axis (D = direction, O = orientation, 1 = set1, 2 = set2). Note that the pattern of results is similar to Fig. 2.

were significant too ($F(1,7) = 7.8$, $P < 0.03$ and $F(1,7) = 17.5$, $P < 0.004$; respectively).

4. Discussion and conclusions

No differences in accuracy were found between the processing of circles or squares. All cued judgments (first responses) were highly accurate, irrespective of the attribute involved. The second attribute judged was reported accurately if it concerned the same surface as the first attribute. All attributes from the uncued surface were reported poorly. This occurred for the two types of cueing employed in the study. In other words, when motion is used to parse the scene into two superimposed but different surfaces, pairs of judgments on the cued surface were performed without interference. The two attributes could even belong to different dimensions or domains like form and motion. However performance was strongly impaired when one of the judgments concerned the unattended surface. Here, adding color as an additional cue for segmentation was associated with a significant trend to improve discrimination accuracy of processing related to the cued surface, and of greater interference for the uncued surface.

These results replicate previous descriptions of the two-object disadvantage in simultaneous perceptual discriminations [2–4,10,13,28,29]. Together with our previous work [24,25], these results indicate that the two-object disadvantage is found for the components of transparent motion, where simple spatial selection (as in attentional ‘spotlight’ models) is not possible. They extend previous results by showing that the parsing accomplished by transparent motion creates restrictions in performing simultaneous discriminations not only for motion attributes. With transparent motion, the ‘two-surface’ interference can be found for combinations of motion and non-motion attributes, or even of two types of non-motion attributes. Similar conclusions had been reached with non-superimposed pairs of objects [6].

However it could be argued that our subjects performed a tracking of individual elements and that the effects we were seeing are space-based. This could be possible if the attentional spotlight shrinks to the regions around the selected elements, consistent with predictions of some spatial models of attention [16,19]. The higher degree of element coherence (80%) used in the form task could have favored the tracking of individual elements. In contrast, for the task of motion direction discrimination it is improbable that subjects have followed this strategy since the motion coherence level used was only 60% (see also [31]). Tracking of individual elements trajectory with this level of coherence could not have produced the accuracy of around 75% corrected for chance (80% uncorrected) found in cued surface trials. The subjects were forced to use a wide attentional window for this task. Importantly, the subjects did not know beforehand which of the attributes they had to report on a given trial. If they had tracked individuals to favor the form task, performance in the motion task would have suffered as it has been demonstrated for switching strategy [3]. Therefore it is not probable that they were tracking individual elements.

On the other hand, our last experiment confirmed that the results discussed above are really due to the advantage of single-object processing. Interference in processing multiple-objects was not avoided when subjects knew beforehand which features were involved and to which surfaces they belonged. Moreover, similarity in the components of pairs, as in the case of 'orientation–orientation' or 'direction–direction' pairs, didn't make the discrimination of attributes placed in different surfaces easier. That is, even when the pair only demanded discrimination within the same processing module, switching between surfaces was associated with a cost. However it was interesting to find that the difference between 'direction–orientation' pair was lower than between 'orientation–direction'. A possible reason for such a difference is an asymmetry in the direction of attentional switching between the global and local levels of hierarchically organized stimuli. Whereas motion discrimination compelled subjects to use a wide attentional window, form discrimination can probably be performed with a narrower window as explained above. In contrast to Experiments 1 and 2, it was possible in principle to program variations in the size of the attentional window in this experiment because subjects knew in advance the kind of judgements they had to perform. As it has been shown before by Kotchoubey et al. [15], the interference effect between local and global level is larger when the local, rather than the global level, is cued. In Kotchoubey's study, shifting attention from local to global characteristics produced a larger increase in reaction time and error rate. In our case the warning at the beginning of the trial not only informed the subject on the identity of the pair for the discrimination but also on the order in which the response should be reported. It's likely that this information had compelled subject attention to the surface containing the first element of the pair. If so, the local level had preference over the global in trials where the 'orientation–direction' pair was cued.

The lack of interference in judging attributes present in the same surface but coming from different domains evinces a cross-domain linkage for features belonging to the attended object. Previous work that found facilitation for the processing of attributes belonging to the same perceptual object has been limited to study the phenomenon inside the same processing module or the same domain. The study of O'Craven et al. [18] has been the only experiment we found in the literature in which a cross-domain linkage of feature processing non-spatially mediated is described. They demonstrated simultaneous fMRI activation in areas of the ventral and dorsal pathways when attributes processed in those areas belonged to the same attended object. However to our knowledge, the results presented here are the first psychophysical demonstration of cross-domain linkage of feature processing.

Moreover, our results refute discrimination-based models of visual attention [1,22]. These models consider that attentional interference is due to competition for the same perceptual analyzers when concurrent discriminations are performed. Therefore, larger similarity between attributes should generate more attentional interference. However in our experiments, interference for motion–motion judgments (that used the same perceptual analyzers) and for motion–form judgments (that used different perceptual analyzers) were equivalent which confirms that interference depends very little on the similarity of two discriminations, but more on whether they concern the same object or not [7–9].

These results are in line with Duncan's integrated competition hypothesis [5]. This hypothesis indicates that once an object gains processing advantage in one neural subsystem, this advantage is transmitted to the rest. In our case — and following Duncan' hypothesis — we could state that once neurons are selectively primed with the cue for squares (controlled competition), the squares take advantage over circles in the subsystem that analyze form (competition within the same subsystem). This advantage is then transferred to neurons that process the direction of the squares in the subsystem analyzing motion (integration between subsystems).

To summarize, attention enhances simultaneous processing of attributes on the attended surface, even when attributes belong to clearly different domains such as form and motion. These results are consistent with and offer additional support to the integrated competition hypothesis [5,27]

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