Object-based selection operates on a grouped array of locations

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In two experiments, space- and object-based selection effects were investigated, using variants of the *ring-cuing* paradigm of Egly and Homa (1984). The results revealed significant cuing modulation for nonring configurations of target locations spanning a range of retinal eccentricities, with the cuing effects independent of eccentricity and confined to the configuration of locations (rather than extending to locations within the space enclosed by the cued configuration). These results are consistent with object-based selection operating on a *grouped spatial array* (Vecera & Farah, 1994). Object selection may be based on a supradimensional saliency map representation of the field, modulated by feature-specific segmentation mechanisms (e.g., an object may be made salient on the basis of its color). Complex objects may be represented by grouped saliency signals. In this way, a two-dimensional spatial (saliency) representation may provide the common format for object-based selection, prior to full object definition.

Recent theories of selective visual attention have sometimes tended to favor the view that visual attention is essentially object based, selecting perceptually delineated and integrated "object" entities from the visual scene for further processing and action (e.g., Baylis & Driver, 1993; Duncan, 1984). On such object-based accounts, perceptual grouping is fundamental to visual scene segmentation and the formation of objects. Neisser (1967) proposed that visual scenes are segmented, initially, into groups (i.e., objects) on the basis of the operation of the Gestalt principles of perceptual organization. Visual attention is then focused on separate objects sequentially for further processing.

This object-based view of visual attention has been contrasted with space-based accounts, according to which selection operates on whatever information is present within a circumscribed spatial region (e.g., Eriksen & Hoffman, 1973; J. E. Hoffman & Nelson, 1981; Posner, 1980; Posner, Snyder, & Davidson, 1980). Thus, for example, Duncan (1984) attempted to demonstrate object-based selection effects in the absence of space-based attentional factors, by presenting two overlapping objects briefly within a central area of 1° of visual angle (which had been estimated to be the narrowest angle of the attentional *zoom lens*). Duncan compared two dual-judgment conditions: report of two attributes of a single object and

report of two attributes each relating to a separate object. He observed an accuracy cost in making dual judgments to two objects, relative to dual judgments to one object, providing evidence for object-based selection.

Although Duncan's (1984) study has been widely accepted as supporting object-based selection, it has been argued, by Vecera and Farah (1994) and Kramer, Weber, and Watson (1997), that the two-object cost in Duncan-like paradigms does involve spatial-attentional mediation. Vecera and Farah advocated a definition of a true object, which was likened to Marr's (1982) spatially invariant three-dimensional *model* representation, as distinct from a mere collection of place tokens (locations) grouped into an objectlike array, likened to Marr's spatially variant *primal sketch* representation. Selection in Duncan's study may not have been truly object based but, rather, based on a mere two-dimensional (2-D) object array. Vecera and Farah investigated this issue in a series of experiments, from which they concluded that selection may be based on either type of representation, depending on the task to be performed (luminance increment detection vs. object attribute judgments). In contrast, Kramer et al., who reinvestigated the findings of Vecera and Farah, argued that the initial selection of objects is essentially location based, in terms of the grouped-spatial-array notion, whatever the task.

Baylis and Driver (1993) also attempted to demonstrate object-based effects, while ruling out space-based factors. They showed that physically identical displays could be parsed as one or two objects, depending only on observers' feature-based perceptual set. In Baylis and Driver's (1993) study, observers made speeded, relative-height

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judgments of two apices on the outline contours of briefly presented solid shapes (a colored [e.g., red] hexagon flanked on either side by pentagons of a different [e.g., green] color). Observers had to make judgments involving a single shape or two shapes, colored by a prespecified target hue (e.g., red) only. Observers had to respond left or right to indicate which apex was the lower of the two critical apices. In the critical condition, the central shape was joined horizontally to the flanking shapes, so that differences in judging one object versus two objects could be assessed by using physically identical stimuli. Regardless of the feature-based set for a given group of observers (*red* or *green*), a between-objects reaction time (RT) cost was found when the two flanking objects were target colored, relative to when the central object was target colored. Baylis and Driver (1993) concluded that determining the relative position of parts of the same object is direct because the parts are represented within a single, object-based system. In contrast, deriving the relative location of parts of two objects is indirect, requiring the computation of a (scene-based) relationship between object-based representations.

However, O'Grady and Müller (2000a; Müller & O'Grady, 1999) have provided evidence that the two-object cost in Baylis and Driver's (1993) paradigm is, in part, attributable to feature-based processes that segment the field into two salient loci of activation on some *overall activation*, or *saliency*, map representation of the scene, determining the allocation priorities for spatial attention (e.g., Koch & Ullman, 1985; Treisman & Sato, 1990; Wolfe, 1994). That is, the two-object RT cost involves a spatial-attentional component: the time required to shift attention from one object locus to the second.

Thus, there is emerging evidence that visual selection involves functionally interrelated space-based and object-based processes and that these processes are modulable by feature-based segmentation processes (for reviews, see Müller & O'Grady, 2000; Schneider, 1993; van der Heijden, 1993).

The two experiments reported in the present study were designed to further examine the interrelationship between object-based and space-based attention, using variants of Egly and Homa's (1984) *ring-cuing* paradigm. Egly and Homa investigated whether spatial attention could be divided simultaneously across multiple locations that were arranged in the form of three differently sized rings around a central fixation point (1°, 2°, 3° of visual angle in radius). The observers' task was to localize a target, which could appear with equal likelihood at any of the eight locations on one of the rings. One ring, on which the target letter was likely to appear, was prespecified in advance by a verbal spatial cue. The results showed that for all eccentricities, the target letter could be localized more accurately when its ring was cued (valid-cue trials) than when it was uncued (invalid-cue trials). This pattern is consistent with a ringlike distribution of attention, supporting the view that attention can be allocated to a configuration of multiple locations around a fixation point.

The ringlike cuing effects reported by Egly and Homa (1984) were reinvestigated by O'Grady and Müller (2000b, Experiment 1), who measured signal detection accuracy, using an independent-decisions design (for methodological details, see Experiment 1, Method section¹). O'Grady and Müller (2000b, Experiment 1) observed that the cuing significantly modulated signal detection sensitivity for the three rings, consistent with Egly and Homa's *ring-based* account of spatial attention. Furthermore, O'Grady and Müller (2000b, Experiment 3) provided evidence that the cuing effects with ring-shaped formations may involve a form of space-based selection—namely, segmentation of the three rings, utilizing secondary depth cues. However, even with depth cues made inconsistent to prevent depth-based segmentation, there remained a reduced but significant cuing modulation. Assuming that a depth-based interpretation of the display was disrupted completely in this condition, the finding of a residual cuing modulation would argue either that spatial attention could indeed be distributed in a 2-D ringlike fashion or that attention could be allocated to any "object" by whatever (feature-based) means it was segmented from the background.

In summary, there is evidence to suggest that spatial attention can be deployed in a configurally flexible, objectlike fashion. However, it is unclear what role the spatial arrangement of the cued locations plays. For example, Kiefer (1988) suggested that humans might be better at attending to spatial arrays which form "meaningful" 2-D shapes (e.g., a ring shape). The present experiments were designed to clarify this issue by examining whether or not the cuing modulation extends to objectlike configurations other than rings. In addition, the type of (object) representation on which selection operates was investigated. Overall, the results were consistent with object-based selection mediated by feature-based segmentation processes and with an object's being represented in this framework as a grouped array in space.

EXPERIMENT 1

With the ring-shaped formations used by Egly and Homa (1984) and O'Grady and Müller (2000b), there was a potential confound of uniform spatial separation from fixation (retinal eccentricity) with "object." To avoid this and to examine whether the cuing modulation extends to objectlike configurations other than rings, displays in the present Experiment 1 consisted of three objects, each defined across three eccentricities, so that any modulation of attention owing to cuing an object could not be attributed to cuing a particular region (uniform distance from fixation). The object-based cuing modulation was expected to be manifest in significantly improved target detectability for a cued object, relative to the same object when uncued (with the effect's being expected to be accompanied by an overall effect of target eccentricity). In other words, the construction of the objects across the three eccentricities, with the possible tar-

get locations within each object varying in terms of their distance from fixation, permitted the notion of an object represented in terms of a grouped spatial array (e.g., Schneider, 1993; Vecera & Farah, 1994) to be tested.

In addition, Experiment 1 varied the *goodness* of the objects presented, with object goodness manipulated by changes in object shape. Edge- (i.e., shape-) based descriptions of the visual image are considered by some to be critical for visual object representation and recognition (e.g., Baylis & Driver, 1995; Biederman, 1987; Driver & Baylis, 1995). According to a generally accepted principle, concavities in the boundary contour of complex objects are likely to signal the points at which component parts of the object intersect (Driver & Baylis, 1995; Gibson, 1994; D. D. Hoffman & Richards, 1984). Furthermore, it has been demonstrated that, if boundary contour segments of complex objects are deleted at regions of concavity, thus omitting critical joints between object parts, recognition performance worsens (Biederman, 1987).

According to Biederman's (1987) theory of object recognition, extreme concavities define points at which whole objects tend to be broken up into object components, which are processed (*identified*) separately and must be reassembled to permit recognition of the complex object to occur. In other words, objects with extreme concavities may be considered to be more fragile or, in terms of Gestalt psychology, less *prägnant*. To examine whether object-based selection depended on the geometrical simplicity of the objects to be attended, the object goodness was manipulated in Experiment 1 by varying the regularity of the objects' outline shape, with "good" (regular) objects being defined by minimal concavities and "bad" (irregular) objects exhibiting more extreme concavities (see Figure 1). Finally, the information by which the likely target objects were cued in Experiment 1 was also varied: cuing was either by global object (2-D) orientation or by orientation plus color. Orientation-plus-color cuing was expected to be more effective than orientation cuing alone, assuming that both types of information combine to enhance the definition of the cued object.

Method

Observers. Sixteen observers (11 women and 5 men, between 19 and 35 years of age) participated in Experiment 1. All the observers had normal or corrected-to-normal vision, and all reported normal color vision. They were paid £5 per hour. The observers were randomly allocated to one of the object-goodness conditions (see below). One observer in the good-object condition started, but failed to complete, the experiment. The data collected for this observer could not be used in the final analyses.

Apparatus. The experiment was run in a completely darkened laboratory. Stimuli were presented on a high-resolution 60-Hz color CRT monitor driven by a Silicon Graphics Iris Indigo Unix workstation. The observers initiated a block of trials by pressing the Enter key on the computer keyboard, and they responded on a trial with the computer mouse. The observers viewed the monitor from a distance of 70 cm, with viewing distance maintained through the use of a chinrest. The brightness of the monitor was adjusted to a comfortable level and remained unchanged throughout the experiment.

Stimuli. On each experimental trial, the following sequence of stimuli was presented on a black monitor background (see Figure 1). A trial started with the presentation of a fixation dot in the screen center and a spatial grid of boxes and connecting lines grouped to form three identical, nonringlike, shapes. The fixation dot was effectively the intersection point of three objects overlapping through their center portions only, with each object spanning the three eccentricities of 1°, 2°, and 3°, both sides of fixation, and each object rotated at a different angle about the center. Each object was formed by a set of 12 connecting lines and 12 superimposed outline boxes (potential target locations). Of these 12 outline boxes, 4 were located at each eccentricity (2 boxes on one side of fixation, 2 on the opposite side). The first object was oriented *vertically*, extending up and down from fixation (primary axis of elongation oriented at 15° and 195° angles clockwise from vertical [0°]); the second object was oriented *horizontally*, extending left and right of fixation (axis of elongation oriented at 75° and 255° angles from vertical); and the third object was oriented *diagonally*, extending down to the right and up to the left from fixation (axis of elongation oriented at 135° and 315° angles from vertical). These objects will be referred to as the *vertical*, *horizontal*, and *diagonal* objects, respectively. A good object had the appearance of a *bow-tie* (central-portion parallel lines with lines either side diverging gradually outward across the three eccentricities from fixation into closed ends). A bad object was identical with a good object for the central portion, but with both ends warped in a clockwise direction, thus producing four extreme concavities that were nonexistent on the good object.

The outline boxes each were 0.31° square, centered on the appropriate object-eccentricity intersection points. Connecting lines were 1 pixel in width. In the orientation-plus-color cuing condition, all the connecting lines and boxes of a given object were of the same hue (with different hues across objects); the three colors used were red, green, and blue (luminances, 2.5, 1.5, and 2.5 cd/m², respectively). In the orientation-only cuing condition, all the connecting lines and boxes were of the same pale gray hue. An object-informative cue consisted of the fixation dot's changing to a small bar oriented at the angle of the cued object's primary axis (the bar subtended 0.24° in length and 0.05° in width and was centered on the screen center coordinates). In the orientation-only cuing condition, the cue bar was of a shade of gray brighter than that of the initial fixation dot. In the orientation-plus-color cuing condition, the cue bar changed its hue to that of the object to be cued (red, green, or blue). On neutral-cue trials, the fixation dot flashed white-black-white for 50 msec and then returned to its initial pale gray hue.

The target stimuli consisted of crosses of line size 0.20°, presented centered inside a number of the outline boxes on the objects of the grid. The mask consisted of 36 crosses, each outlined by a miniature box of the same dimensions (0.20° square), one presented in each grid box. Each masking stimulus was presented at the exact pixel coordinates of a potentially preceding target stimulus.

A visual probe highlighted the object to be responded to. A set of four response alternatives (click panels) and the mouse pointer appeared in the lower part of the monitor. The set of click panels consisted of the following response categories (from left to right): NO CERTAIN, NO UNCERTAIN, YES UNCERTAIN, and YES CERTAIN.

Target exposure durations. For all the observers, the starting target exposure durations were determined during two initial practice sessions (identical task to that in the main experiment) so that observers could discriminate target presence/absence in the neutral condition with 60%–70% accuracy in terms of the signal detection sensitivity parameter A_z (see below). At the end of practice, the observers had achieved neutral-condition A_z values within the range of .558–.750 (mean, .641). Across all observers, the criterion exposure durations (with which observers started and continued the main experiment) were within the range of 50–117 msec (mean, 83 msec).

Design. In Experiment 1, we used a mixed design involving within-subjects factors of cue condition (orientation only and orientation

Figure 1. Illustration of good-object (left) and bad-object (right) displays presented in Experiment 1. The top displays illustrate a central cue, a bar symbol oriented in the same direction as the major axis of the cued object (in color-plus-orientation cuing conditions, the bar cue also took on the color of the cued object). In the good-object display, a target appears on the cued (vertical) object and one uncued (diagonal) object; in the bad-object display, a target appears only on one uncued object. The bottom displays show the poststimulus masks, together with a vertical-object probe (highlighting).

plus color), cued object (neutral, vertical, horizontal, and diagonal), and judged object (vertical, horizontal, and diagonal). Object goodness (good or bad) was a between-subjects factor. Of all the trials, 83% presented a spatially informative cue, and 17% a neutral cue.

Experiment 1 used an independent-decisions design, adopted from Downing (1988) and Müller and Humphreys (1991), to ensure that observers made independent signal detection (target/no-target) responses to cued and uncued objects.² On informative-cue trials, the target and no-target incidents were distributed on the cued object and the two uncued objects in such a way that the presence (or absence) of a target on the cued object had no correlation with target

presence (or absence) on either of the uncued objects; similarly, on neutral trials, the presence/absence of a target on one object had no influence on target presence/absence on either of the other objects.

For informative-cue trials, the combination of object (cued, uncued₁, and uncued₂) with target (present or absent) required 32 valid trials and 8 invalid trials to give a cue validity of 80%; for neutral-cue trials, the corresponding number of trials was 8 (see the Appendix for details of how the basic permutation of 32 [valid] + 8 [invalid] + 8 [neutral] = 48 trials was formed). A target could appear on one of the objects, on each of any pair of objects simultaneously, on all three objects simultaneously, or not at all. The maximum num-

ber of targets on a given trial, being three, was within the estimated capacity of visual short-term memory (VSTM; see, e.g., Fisher, 1982, 1984; Yantis & Johnson, 1990), removing the possibility of VSTM confounds. At most, one target was presented on a given object, unpredictably in any 1 of the 12 relevant boxes. Since all the locations on a given object were equally likely to contain a target, the observers could gain no advantage by repositioning their eyes during the cue presentation period. For trials with informative cues, on the uncued objects, there could be two targets (one on each object), a target on one object and none on the other (or vice versa), or no targets on either object. Regardless of target presence or absence on the two uncued objects, under valid cuing conditions, a target was always present on the cued object; under invalid cuing conditions, a target was never present on the cued object.

The cued object (vertical, horizontal, or diagonal) and the color assignment to the three objects were fixed throughout a block of trials, to help observers set themselves consistently for a given object. However, the assignments varied across blocks—that is, within a session, each object was cued three times across the nine blocks. Across trials, each object (vertical, horizontal, and diagonal) was equally often red, green, and blue. Therefore, an extra multiple of three was required of the basic permutation of 48 trials. In addition, to ease the memory load, observers were required to produce only a single response to a single object on a given trial. However, the exact same trial display was presented twice more, so that sensitivity for each of the other two objects could be tested under identical cued object and target object conditions (the total number of trials accordingly was tripled). Furthermore, there were 12 boxes on each object, in one of which a target could appear, so the permutation was again increased by a multiple of 12. With the different cue color to cued object assignments pseudorandomized across the two cue conditions (orientation only and orientation plus color), a total of $(48 \times 3 \times 3 \times 12)/2 = 2,592$ trials was needed for each observer under a given cue condition (i.e., 5,184 trials under both cue conditions). These were divided into six sessions, each consisting of nine blocks of 48 trials.

Within a block, each object (vertical, horizontal, or diagonal) was probed for response for approximately the same number of trials. On informative-cue trials, the probing of each object, cued or uncued, was unpredictable. Within a session, the probe distributions reflected the proportions of validly cued, invalidly cued, and neutral trials. For a given session, the 48 basic permutation trials (incorporating valid, invalid, and neutral trials and probe assignments) were pseudorandomized within blocks. The cue condition (orientation only or orientation plus color) was kept constant throughout a session but varied across sessions (with order counterbalanced for the observers in each of the two object-goodness groups).

Procedure. The fixation dot and the empty grid were presented together for 500 msec. The central cue onset then occurred. The cue remained on until the end of a trial. The target display was presented 1,500 msec after cue onset. The targets were presented briefly for a predetermined exposure duration, terminated by the contour pattern mask. One second after mask onset (with the mask remaining visible), the visual probe and response click panels with the mouse pointer appeared simultaneously. Of the response alternatives, *yes* and *no* referred to the decision as to whether a target was present or absent on the probed object and *certain* and *uncertain* to the confidence associated with that decision. In all the conditions, the observers responded by selecting and mouse-clicking the appropriate panel. The mask, probe, response panels, and mouse pointer stayed on the screen until a mouse click was recorded. There was then a blank interval of 1 sec until the beginning of the next trial.

The observers were randomly allocated to one of the object-goodness conditions. Each observer served in three practice sessions (each 45 min) followed by 12 experimental sessions (each 45 min) performed during the same week. Each (practice or experimental) session started unpredictably with a vertical cued, hori-

zontal cued, or diagonal cued block. At the beginning of each block, a written message was displayed to the observers, informing them about the cued object and cue color throughout the next block of trials. The observers were instructed to use the central cue orientation and the cue color to allocate their attention to the cued object, maintaining fixation on the cue throughout a trial until the response stage, and to concentrate on response accuracy rather than on speed. In the event of a neutral, no-color cue, observers were told to “relax” their attention uniformly over the entire display of three objects. They were also informed that, on a given trial, an individual object would contain either no target or one target only and that, on the three objects taken together, there would be a total number of zero, one, two, or three targets. The observers were informed that, on any trial, the presence of a target on one object had no influence on target presence/absence on either of the other two objects. If they had to guess, they could use the knowledge that, on trials with informative cues, target likelihood for the cued object was 80%, whereas target likelihood for either uncued object was 50%, and that on neutral trials, target likelihood for any given object was 50%.

Analysis. The sensitivity parameter A_z was used as the accuracy measure. A_z is the area under the receiver-operating characteristic curve computed on the assumption of Gaussian (but not necessarily equal variance) signal and signal-plus-noise distributions. Estimates of A_z were obtained for each observer under each experimental condition, based on the maximum likelihood approach for confidence-rating method data developed by Dorfman and Alf (1969).

The cuing effects were examined in terms of benefits plus costs (i.e., the accuracy difference between valid- and invalid-trial conditions), rather than benefits and costs relative to the neutral-trial condition (see Jonides & Mack, 1984, for a detailed consideration of “the cost and benefit of cost and benefit” measures in cuing paradigms).³

Results

Table 1 presents the A_z values for each of three judged objects (horizontal, diagonal, and vertical) under each of four cued-object conditions (neutral, horizontal cued, diagonal cued, and vertical cued) for the average observer; the values are shown separately for each combination of good/bad object (between-subjects factor) with orientation-only/orientation-plus-color cuing condition.

The A_z data were analyzed with a mixed (one-between, three-within) analysis of variance (ANOVA). There were significant main effects of judged object [$F(2,26) = 26.38$, $MS_e = 0.0039$, $p < .0001$], with detection accuracy being greater for horizontal objects, relative to diagonal and vertical objects (.844, .822, and .781, respectively), and of object goodness [$F(1,13) = 5.51$, $MS_e = 0.1283$, $p < .05$], with detection accuracy being greater for good than for bad objects (.869 vs. .766). The main effect of cued object was marginally significant [$F(2,26) = 2.82$, $MS_e = 0.0021$, $p < .10$], whereas the main effect of cue condition was nonsignificant ($F < 1$; orientation only vs. orientation plus color: .831 vs. .804). Furthermore, there was a significant interaction between cued object and judged object [$F(4,52) = 14.64$, $MS_e = 0.003$, $p < .0001$], indicating a reliable cuing modulation (overall cuing costs plus benefits: .054). Most important, there was a significant interaction between cued object, judged object, and object goodness [$F(4,52) = 3.71$, $MS_e = 0.0030$, $p < .01$], indicating a greater cuing effect for bad objects than for good objects (.028 vs. .079). No other effects were sig-

Table 1
Mean Accuracy (A_z Scores) for Each of the Three Judged Objects
(Horizontal, Diagonal, and Vertical), When Either Good or Bad Objects
Were Presented, Under Each of Four Cued-Object Conditions
(Neutral, Horizontal Cued, Diagonal Cued, and Vertical Cued), in the
Orientation-Only and Orientation-Plus-Color Cuing Conditions of Experiment 1

Cued Object	Good Judged Object				Bad Judged Object			
	Horizontal	Diagonal	Vertical	<i>M</i>	Horizontal	Diagonal	Vertical	<i>M</i>
Orientation-Only Cue								
Neutral	.895	.907	.887	.896	.820	.735	.764	.773
Horizontal	.933	.912	.851	.899	.859	.746	.747	.784
Diagonal	.910	.902	.849	.887	.806	.700	.760	.760
Vertical	.898	.907	.874	.893	.762	.737	.780	.760
Mean*	.914	.907	.858	.893	.799	.763	.742	.768
Cuing effect†	.029	-.008	.024	.015	.090	.064	.056	.070
Orientation-Plus-Color Cue								
Neutral	.870	.867	.828	.855	.828	.746	.751	.775
Horizontal	.913	.855	.784	.851	.878	.717	.711	.769
Diagonal	.859	.875	.768	.834	.751	.810	.706	.756
Vertical	.863	.850	.824	.846	.775	.743	.779	.766
Mean*	.878	.860	.792	.844	.801	.757	.732	.763
Cuing effect†	.052	.022	.048	.041	.115	.080	.070	.088

Note—Valid-trial accuracy is given in boldface. *Excluding neutral condition. †Average costs plus benefits.

nificant [all F s < 1, except for a marginally significant cue condition $\times$ cued object $\times$ judged object interaction, $F(4,52) = 2.36$, $MS_e = 0.0012$, $p < .075$].

As can be seen from Table 1 (see the cuing effects), there were losses in target detectability for a given object when uncued, relative to target detectability for the same object when cued. This pattern was evident for all objects (vertical, horizontal, and diagonal), no matter whether good or bad and regardless of whether cuing was by orientation only or by orientation plus color. Furthermore, although the cue condition $\times$ cued object $\times$ judged object interaction was only marginally significant in the overall ANOVA (see above), an analysis of the cost-plus-benefit data only, with uncued-trial accuracy averaged across the two uncued objects, revealed the effect of the cue on the size of the cuing modulation to be significant [$F(1,13) = 6.93$, $MS_e = 0.0015$, $p < .050$]: the benefits plus costs were slightly, but consistently, greater with orientation-plus-color cues than with orientation-only cues (.065 vs. .043). No other effects (except that of object goodness) were revealed to be significant by the costs-plus-benefits analysis.

One further analysis was carried out to ascertain whether the significant *object-based* cuing modulation reported above applied equally to all three box eccentricities for a given object or whether it was due to particular eccentricities only (this was not clear from the above analyses, which were based on accuracy measures that combined detection accuracy across the three eccentricities for each object). If the cuing modulation is indeed object based, it should be evident (and equivalent) for each box eccentricity within an object (although overall accuracy would, of course, be expected to be dependent on retinal eccentricity). The results of the analy-

sis involving box eccentricity are summarized in Table 2, which presents the A_z values for each eccentricity under orientation-only and orientation-plus-color cue conditions across the three cued-object conditions (horizontal cued, diagonal cued, and vertical cued).

The eccentricity data were subjected to a mixed ANOVA, with main terms of object goodness (between-factors), cued object, judged object, target eccentricity, and cue condition (within-factors). The judged object effect [$F(2,26) = 26.53$, $MS_e = 0.0105$, $p < .0001$] and the cued object $\times$ judged object interaction [the cuing effect; $F(4,52) = 15.96$, $MS_e = 0.0099$, $p < .0001$] were significant. More interesting, in the present context, there was a highly significant main effect of target eccentricity, as was expected [$F(2,26) = 38.39$, $MS_e = 0.0090$, $p < .0001$; overall accuracy at 1°, 2°, and 3° eccentricities: .853, .828, and .784, respectively]. However, the cuing effects were not influenced by target eccentricity (there were no interactions involving target eccentricity, cued object, and judged object; all F s < 2).⁴

Discussion

In summary, the cuing modulation observed in Experiment 1 was not affected by the eccentricity of the boxes making up an object, indicating that the cuing modulation is indeed object based, influencing sensitivity for all the components of a grouped array of boxes. This is consistent with Egly, Driver, and Rafal (1994), who also attempted to dissociate space-based from object-based components of selection. They used a luminance increment detection task to probe the allocation of attention within a single display of two spatially separate rectangles presented either above and below or to the left and right of fixation. The terminal section of one of the rec-

Table 2
Mean Accuracy (A_z Scores) for Cued and Uncued Objects
(Averaged Across Uncued Objects) as a Function of Target
Eccentricity (1°, 2°, and 3°), Separately for the Orientation-Only
and Orientation-Plus-Color Cue Conditions of Experiment 1

Objects	Good Objects			Bad Objects		
	1°	2°	3°	1°	2°	3°
Orientation Only						
Cued	.907	.908	.883	.848	.816	.780
Uncued	.887	.888	.871	.786	.746	.687
Mean	.897	.898	.877	.817	.781	.734
Cuing effect*	.020	.020	.012	.062	.070	.093
Orientation Plus Color						
Cued	.902	.881	.823	.867	.824	.775
Uncued	.846	.835	.790	.782	.727	.660
Mean	.874	.858	.807	.825	.776	.718
Cuing effect*	.056	.046	.033	.085	.097	.115

*Average costs plus benefits.

tangles was cued, and a target square was presented filling in the cued end of the cued rectangle (valid target; 75%), the opposite end of the cued rectangle (invalid within-object target), or the end of the uncued rectangle that was as distant from the location of the cue as was the opposite end of the cued rectangle (invalid between-objects target). The simple detection RTs were faster for validly cued targets than for invalidly cued targets. Furthermore, with invalidly cued targets, RTs were faster to targets at the opposite end of the cued object (involving "a purely spatial component of selection") than to targets at the equidistant end of the uncued rectangle (involving an across-object shift of attention). However, the paradigm of Egly et al. did not conclusively rule out space-based selection—specifically, a spatial-attentional preference for the upper or lower or, alternatively, the left or right hemifield that contained the cued rectangle (with spatial attention centered on the cued end of the rectangle). Such an account can be ruled out unequivocally for Experiment 1, because all cued (and uncued) objects were symmetrical around fixation.

One further interesting finding of Experiment 1 was that accuracy tended to be higher overall for good than for bad objects (object-informative cue trials only: .869 vs. .766), whereas the cuing modulation was greater for bad than for good objects (.079 vs. .028). The latter finding runs counter to the intuition that object-based cuing effects would be larger for good (i.e., easily selectable) objects than for bad objects. A speculative account of why the cuing modulation might be greater for bad objects will be outlined in the General Discussion section.

Furthermore, the cuing modulation in Experiment 1 was somewhat larger with orientation-plus-color cues than with orientation-only cues (.065 vs. .043). An advantage for orientation-plus-color cuing was expected on the basis of data from the O'Grady and Müller (2000b) study (Experiments 2 and 3), which compared the relative efficiencies of color- and depth-based segmentation strategies. However, it is not clear whether this advantage

is due to a synergy between orientation- and color-based cuing mechanisms or whether it is due to color cuing only. The data and the arrangement of objects in Experiment 1 do not permit us to distinguish between these alternatives, because individual objects were defined by a particular (*intrinsic*, global) orientation, whether they were colored or not.

A relatively minor finding of Experiment 1 was that accuracy was greater for horizontally oriented objects than for diagonally and, most clearly, vertically oriented objects. Although this may appear to be an odd difference, suggestive of an arbitrary bias, there may be an objective reason for this preference. For example, object construction mechanisms might assume implicitly that, for elongated objects, the canonical, or default, orientation imposed to derive an axis-based object description (Marr, 1982) is horizontal.

EXPERIMENT 2

In Experiment 1, all the potential target locations were outside the region of object intersection, so that a given potential target location on one object could not happen to fall within the space enclosed by another object. Thus, it was not possible to decide whether the attentional modulation affected target detectability only at locations on the cued object's boundary contour (object = grouped spatial array; see Schneider, 1993; Vecera & Farah, 1994) or also at locations on an uncued object located within the spatial region defined by the boundary contour of the cued object (object = delineated spatial region). Experiment 2 was designed to distinguish between these alternatives.

The displays in Experiment 2 (see Figure 2) comprised two intersecting objects. According to the delineated-spatial-region account, target detectability for the inner locations of the uncued object, which are enclosed within the region described by the cued object, should be as high as that for the inner locations of the cued object. In contrast, according to the grouped-spatial-array account, there should be no such interaction between inner/outer location and cued/uncued object. There was a further manipulation: Recall that, in the orientation-plus-color cuing condition of Experiment 1, each object could be distinguished from the others on the basis of a common color and the connecting lines between the boxes, which endowed the property of closure on each object (cf. the Gestalt principle of *uniform connectedness*, recently proposed by Palmer, 1992, and Palmer & Rock, 1994). In order to test for object-based cuing effects based solely on grouping by common color, Experiment 2 compared two conditions in which the lines connecting the boxes of each object either remained (closed-object condition) or were removed (unclosed-object condition).

Method

Observers. Four observers (3 women and 1 man, between 19 and 29 years of age) participated in Experiment 2. All the observers had normal or corrected-to-normal vision, and all reported normal color vision.

Figure 2. Illustration of closed-object (left and middle) and unclosed-object (right) displays presented in Experiment 2. In the top displays, a central colored (e.g., red) dot cues the like-colored object (e.g., the vertical rectangle); also, various targets (crosses) are shown appearing at inner and outer cued and uncued object locations. The bottom displays show poststimulus masks, together with a probe (highlighting) to a pair of inner or outer cued or uncued object locations.

Stimuli. A trial started with the presentation of a fixation dot in the screen center, as well as a spatial grid of boxes and, in the closed-object condition, connecting lines, grouped to form two identical rectangular objects, one oriented vertically and the other horizontally and one red and the other green. An object was formed by a set of six outline boxes (marking potential target locations) and (in the closed-object condition only) six connecting lines. Of these, just two were located within the object-part intersecting with the other object (inner part), and the remaining four were located outside the portion of intersection (outer part). The eccentricity of the inner boxes was 0.88° , and that of the outer boxes 1.95° ; box size was 0.31° . The central object cue was either red or green. Zero, one, two, or three target crosses could appear briefly on the cued object, the uncued object, or both objects. Thus, only three targets at the most were presented on a given object. As previously, the mask consisted of cross-plus-box stimuli, one stimulus appearing in each of the 12 grid boxes.

Target exposure durations. All the observers started practice with a 150-msec target exposure, stepping down to 100, 83, 67, and 50 msec. The criterion exposure durations with which they undertook the main experiment were within the range of 67–117 msec (mean, 90 msec).

Design and Procedure. Factors were object closure (closed or unclosed), judged object (vertical or horizontal), part-judgment (inner location vs. outer location judgment), and cue validity (judged object cued vs. uncued). All the observers performed all the experimental conditions. Cue color and object closure condition orderings were counterbalanced across observers. Cued object ordering (vertical cued first or horizontal cued first) was counterbalanced

across sessions and observers. For the purposes of target presentation and response, a given object was divided into three pairs of boxes (object parts): the horizontal object into the left-outer, inner, and right-outer pairs, and the vertical object into the upper, inner, and lower pairs. A target could appear on one of the object parts, on each of two object parts, or on each of the three object parts. The likelihood of target presence was (independently) 50% in any part on each object, regardless of which object was cued. Valid-cue trials were distinguished from invalid-cue trials only by a greater proportion of responses being made to the cued object (75%) than to the uncued object (25%).

The fixation dot and the empty grid were presented together for 500 msec. The object cue was then presented. The target(s) appeared 1,500 msec after cue onset and was terminated by the mask. After 1 sec, the observers were probed to make a target presence/absence response to a particular part (pair of boxes) of either the cued or the uncued object, with the response-critical boxes being highlighted by their color's (red or green) turning white. Each observer served in eight experimental sessions, consisting of 3,840 trials overall. At the beginning of each session, the observers were visually informed of the cue (red or green). The cued object was horizontal during the first half of a session (240 trials) and vertical during the second half (240 trials), or vice versa. During initial instructions, the observers were told that they should use the cue color to allocate their attention to the cued object. The observers were also informed that, on a given trial, an individual object part would contain either no target or one target only; that, in the two objects combined, there would be a total of no target at all or one, two, three, four, five, or six targets; that, for a given object, the presence of a target on one

Table 3
Mean Accuracy (A_z scores) for Inner Location and Outer Location
Judgments Separately for the Two Judged Objects (Vertical, Horizontal),
as Well as the Two Objects Combined, Under Each Cue Validity Condition
(Judged Object Cued, Uncued) in Experiment 2

Judged Object	Closed Objects			Unclosed Objects			Overall
	Vertical	Horizontal	Mean	Vertical	Horizontal	Mean	
Cued object							
Inner	.820	.821	.821	.816	.824	.820	.821
Outer	.683	.739	.711	.676	.756	.716	.714
+Inner	.137	.082	.110	.189	.068	.104	.107
Uncued object							
Inner	.726	.751	.739	.744	.693	.718	.729
Outer	.621	.697	.659	.599	.648	.624	.642
+Inner	.105	.054	.080	.145	.045	.094	.087
Cuing effect*							
Inner	.094	.070	.082	.072	.131	.102	.092
Outer	.062	.042	.052	.077	.108	.092	.072

Note—Inner/Outer, inner/outer object location; +Inner, inner location advantage.

*Costs plus benefits.

part had no influence on target presence/absence on any other part; and that the presence of target(s) on the cued object had no influence on target presence/absence on the uncued objects, although more responses would have to be made to the cued object than to the uncued object.

Results

Table 3 gives the average A_z scores of inner location and outer location part judgments separately for the two judged objects, as well as for the two objects combined, under each cue validity condition. The scores for the closed- and unclosed-object conditions are presented on the left and right, respectively.

The A_z data were examined with a four-way ANOVA. There were significant main effects of cue validity [$F(1,3) = 12.00$, $MS_e = 0.0090$, $p < .050$] and of part judgment [$F(1,3) = 17.68$, $MS_e = 0.0085$, $p < .025$]. Targets were detected more accurately when they appeared on a cued object, relative to an uncued object (overall cuing effect, .082), and when they appeared on inner object parts, rather than on outer parts (overall inner part advantage, .097). There was also a significant interaction between judged object and part judgment [$F(1,3) = 82.27$, $MS_e = 0.0002$, $p < .005$], merely indicating a greater inner part advantage for the vertical object (.144 vs. .062). However, the cue validity $\times$ part judgment interaction was not significant [$F(1,3) = 2.78$], and there were no effects involving object closure (in particular, the object closure $\times$ cue validity $\times$ part judgment interaction was not significant, $F < 1$).

Discussion

The most important finding was that the cuing effects were equivalent for inner part and outer part judgments. This finding is consistent with the notion that object-based selection operates on grouped spatial arrays, rather than on delineated (enclosed) spatial regions. According

to the latter account, one would have expected the cuing effect to be reduced for inner part judgments relative to outer part judgments, since the inner part boxes of the uncued object were enclosed by the cued object.⁵ The present pattern of effects parallels the results obtained by Yantis (1992), in a multielement visual-tracking study, that false alarms to (nontarget) probes inside a to-be-tracked virtual polygon were not significantly different from those to probes outside the polygon. Interestingly, in the present experiment, removing the lines connecting the boxes did not affect this finding (see also Yantis, 1992, who presented unconnected to-be-tracked polygon elements), suggesting that color similarity alone was sufficient to produce distinct grouped spatial arrays, to one of which attention could be directed selectively.⁶ However, one possibility that was not ruled out by the present experiment was that, owing to the color similarity of the uncued object parts (and their dissimilarity to the cued object parts), the inner (as well as the outer) part of the uncued object was inhibited perceptually, so that it was not (or only very weakly) represented within the spatial region enclosed by the cued object. Further work with non-colored stimuli is necessary to rule out such an account.

GENERAL DISCUSSION

The present experiments were designed to examine the relationship between space-based and object-based selection. Experiment 1 investigated whether attentional selection was object based, rather than specifically ring based. Substantial cuing effects were demonstrated, independently of target eccentricity. The cuing effects were larger for bad-shaped than for good-shaped objects, and they were larger with orientation-plus-color cues than with orientation cues alone. The results supported the idea that selection is object based, with color- and

orientation-based segmentation combining to permit attention to be deployed flexibly to objects of any shape defined across various retinal eccentricities. Experiment 2 was designed to investigate further whether attentional selection was object based, either in terms of an object's being a grouped spatial array (see Vecera & Farah, 1994) or in terms of an object's describing a bounded spatial region. The results were consistent with the grouped-spatial-array account, independent of whether each object was closed or unclosed.

Space-Based and Object-Based Selection

The present experiments are consistent with the idea that attention may be allocated flexibly to any shaped region of a display centered on fixation. This and the other evidence discussed below support the position that selection is object based within the framework of a grouped-spatial-array representation that incorporates information from a variety of stimulus dimensions, such as color and orientation. Color and orientation feature information may be used by special purpose mechanisms to segment complex displays into separate units that may form the "objects" for attentional selection. It is interesting in this context that color information added to orientation information appeared to enhance object selection in Experiment 1. But it remained uncertain whether this cuing advantage was due to a combination of orientation- and color-based segmentation mechanisms or whether it was due to color cuing only (dominating orientation cuing). Humphreys and Boucart (1997) argued that form (including global orientation) and color are independent stimulus domains for selection, supported by independent processing pathways, but that selection by color can involve inhibition of the form pathway. Applied to Experiment 1, the provision of salient color cues may have inhibited (dominated) the use of orientation cues. Whatever the precise relationship between the two types of cue information, what is interesting is that the global orientation of a grouped array of objects can serve at all as an effective selection cue when presented alone (see, e.g., Jolicœur, 1992; McMullen, Hamm, & Jolicœur, 1995).

Another finding supports the notion of object-based selection linked to a spatial (saliency) representation: In both experiments, target detection was facilitated by selection of a grouped array of location markers according to a criterion (orientation plus color, or orientation only) unrelated to the target-defining properties (simple luminance increments). Therefore, the present results are consistent with the idea that some common format—that is, some form of object representation—is fundamental to visual selection. Experiment 2 showed that enhanced target detectability that was due to "object" cuing was restricted to the box components of the cued configuration, rather than extending to components of the uncued configuration inside the spatial region delineated by that cued. Thus, taken together, the results of the present experiments provide strong support for the view that cuing effects that may be interpreted as 2-D space-based se-

lection effects may rather be related to object-based selection (Duncan, 1984; O'Grady & Müller, 2000b), with attention being malleable to an object's shape (*grouped spatial array*; Vecera & Farah, 1994).

One further interesting finding in Experiment 1 was that the cuing effect related to object-based selection was reduced for good (simple) relative to bad (complex) objects. Although seemingly counterintuitive, this pattern of effects is analogous to the finding that even simple, preattentively registered *feature* targets (such as simple luminance increments) show a cuing effect, which is, however, reduced in comparison with more complex *conjunction* targets that require attention to be coded (e.g., Cheal & Lyon, 1992; Müller & Humphreys, 1991; Shaw, 1984). A speculative account might work along the following lines. Good objects are constructed preattentively (e.g., Duncan & Humphreys, 1989), whereas bad objects require attention to be assembled into a coherent representation (e.g., Treisman & Gelade, 1980). Therefore, one good (the cued) object may be selected, whereas the uncued good objects may be monitored efficiently for the occurrence of a target event in the background (because there is no perceptual load to construct them). However, attention is required (hence, the cuing advantage) to assemble the bad object to be selected, leaving the uncued bad objects ill-formed and disassembled, so that they cannot be efficiently monitored for target events. This account draws on the idea advanced by Lavie (1995) that the perceptual load of relevant information determines the selective processing of irrelevant information. Further work is required to investigate the causes of the differential cuing modulation for good and bad objects.

Attempt at a Theoretical Integration

The present findings suggest a relationship between feature- (e.g., color-) based segmentation mechanisms and object-based selection. According to the findings of O'Grady and Müller (2000b), space-based (e.g., depth-based) selection also is involved in this relationship. Object features are processed preattentively and in parallel by a number of independent mechanisms that converge on, and eventually complete, an object definition. However, object-based selection processes may be initiated—that is, object-based representations can provide a common format for selection, prior to complete object definition. This is in contrast to Duncan's (1996) *strong* object-based selection position, according to which "the different attributes of an object are selected together for control of behavior" (p. 553). According to the alternative, *weak* object-based selection position, not all the features related to the object in question need to be processed completely for object-based selection to occur. This assumption is central to the *dimension-weighting account* of Müller and his colleagues (e.g., Müller, Heller, & Ziegler, 1995; Müller & O'Grady, 2000).

The idea that object-based selection operates via a 2-D saliency map (essentially a space-based representation)

has been discussed before (e.g., Schneider, 1993; Treisman & Sato, 1990; Wolfe, 1994). For complex objects that consist of components at different locations, the local 2-D part specification is integral to global object structure, and selection is based on the grouped array of 2-D saliency signals (i.e., the global object). This grouped array may be determined by feature-based segmentation mechanisms so that only (or preferentially) items in a particular color, for example, are enabled to activate the overall saliency representation (see, e.g., Folk, Remington, & Wright, 1994).⁷

In summary, the findings of the present experiments are at variance with conventional *position-special* theories and strong object-based theories of selective attention. Instead, the findings favor a model postulating object-based selection influenced by feature-based processing mechanisms, while operating from a 2-D spatial representation (grouped saliency signals representing complex objects).

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2. To illustrate the importance of the independent decisions, suppose that a target on an uncued object captures attention but that the observer has to make a target/no-target decision concerning the cued object. When displays contain at most one target (i.e., without an independent-decisions design), an observer probably could infer from the detection of a target on an uncued object (attention capture; see, e.g., Yantis, 1993) that the cued object did not contain a target and, consequently, give a negative response. Such inferred judgments would confound the estimates of perceptual sensitivity.
3. Valid- and invalid-trial accuracy showed a clear pattern of benefits and costs relative to neutral-trial accuracy in all experimental (object goodness $\times$ cue) conditions (good object $\times$ orientation-only cue: .903, .896, and .888 accuracy for valid, neutral, and invalid trials, respectively; good object $\times$ orientation-plus-color cue: .870, .855, and .830; bad object $\times$ orientation-only cue: .815, .773, and .745; bad object $\times$ orientation-plus-color cue: .822, .775, and .733). Combined across the four conditions, the benefits and costs were .028 and .026, respectively.
4. There were several further significant effects involving target eccentricity: target eccentricity $\times$ judged-object interaction, $F(4,52) = 10.27$, $MS_e = 0.0029$, $p < .0001$, reflecting a steeper decrease in detection accuracy with increasing eccentricity for diagonal objects than for vertical and horizontal objects; target eccentricity $\times$ cue condition interaction, $F(2,26) = 9.11$, $MS_e = 0.0022$, $p < .005$, indicating a steeper decrease in detection accuracy in the orientation-plus-color condition (1° , 2° , and 3° accuracies for the orientation-only and orientation-plus-color conditions, respectively: .857, .840, and .806, and .850, .817, and .763); target eccentricity $\times$ object goodness interaction, $F(2,26) = 6.72$, $MS_e = 0.0090$, $p < .01$.
5. A tendency for the inner part cuing effect (.092) to be greater than the outer part effect (.072) would argue further against the *object = delineated spatial region* account. Since estimates were obtained not only of the A_c values, but also of their associated variances for each observer under each experimental condition, it was possible to compare the critical-condition A_c scores, using within-subjects z tests (Dorfman & Alf, 1969). These tests revealed target detectability to be significantly ($p < .001$) lower for the inner locations of uncued objects than for the inner locations of cued objects, for all (4 [observers] $\times$ 4 [closed/unclosed $\times$ vertical/horizontal object conditions] = 16) comparisons except one (Observer 2, unclosed vertical object). In contrast, only 12 of the 16 comparisons for the outer locations were significant, resulting in a somewhat reduced overall cuing effect for outer objects parts, as compared with inner object parts.
6. The only (nonsignificant) effect of object closure appeared to be the slightly reduced overall judgment accuracy for the uncued object in the unclosed object condition (.671 vs. .699; i.e., uncued unclosed objects tended to be less accessible to judgment, perhaps suggesting a role for attention in strengthening similarity-based grouping of object components).
7. This could explain why object location may be processed prior to object identity (see, e.g., Johnston & Pashler, 1990), because explicit access to the target-defining features is secondary, even though they determine selection in the first place by contributing to the computation of a featurally neutral saliency representation.

NOTES

1. Egly and Homa (1984) measured only hit and miss rates under conditions of stimulus uncertainty (brief target exposure durations terminated by postdisplay masks), which resulted in high error (miss) rates and a fair amount of guessing. Consequently, as has been suggested by Juola, Crouch, and Cocklin (1987), it was possible that observers were biased in allocating guesses to the cued (likely target) object, "improving" response accuracy for cued objects and "impairing" it for uncued objects. As a result of such a guessing strategy, false alarm rates, had they been measured, would also have been increased for cued object locations and decreased for uncued object locations, thus reducing the magnitude of the cuing effects. In contrast, O'Grady and Müller (2000b) presented target displays that could contain multiple targets occurring uncorrelated on cued and uncued objects, permitting independent decision making. See Downing (1988) and Müller and Humphreys (1991) for a detailed consideration of the need for independent decision making in spatial cuing studies measuring signal detection accuracy (see also note 2).

APPENDIX

Table A1
Basic Permutation of Target-Present (1) and Target-Absent (0) Incidents on
Each of the Cued and the Two Uncued Objects Under Valid- and Invalid-Cuing
Conditions, on Trials With Spatially Informative Cues in Experiment 1

Trial <i>N</i>	Judged Object		
	Cued Object	Uncued Object ₁	Uncued Object ₂
Valid Trials (32/40 = 80%)			
1	1	1	1
2	1	1	0
3	1	0	1
4	1	0	0
.	.	.	etc. (repeated for a further 28 trials)
Invalid Trials (8/40 = 20%)			
33	0	1	1
34	0	1	0
35	0	0	1
36	0	0	0
.	.	.	etc. (repeated for a further 4 trials)
Likelihood of Target Presence on Each Object (Across Trials)			
(40 trials)	32/40	20/40	20/40

Table A2
Basic Permutation of Target-Present (1) and Target-Absent (0)
Incidents on Each of the Horizontal, Diagonal, and
Vertical Objects, on Neutral Trials in Experiment 1

Trial <i>N</i>	Judged Object		
	Horizontal	Diagonal	Vertical
41	1	1	1
42	1	1	0
43	1	0	1
44	1	0	0
45	0	1	1
46	0	1	0
47	0	0	1
48	0	0	0
Likelihood of Target Presence on Each Object (Across Trials)			
	4/8	4/8	4/8

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