

Effect of Surface Medium on Visual Search for Orientation and Size Features

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By using a visual search task, this study examined the encoding of orientation and size for stimuli defined in five different surface media: luminance, color, texture, relative motion, and binocular disparity. Results indicated a spatially parallel analysis of size and orientation features for all surface media, with the possible exception of binocular disparity. The data also revealed a search rate asymmetry in the orientation task for all media: Parallel or shallow search functions were obtained for oblique targets in vertical distractors, whereas steeper serial search functions were obtained for vertical targets in oblique distractors. No consistent asymmetry was found for the large and small targets in the size task. There seemed to be common principles of coding in all these different media, suggesting either a single analysis of shape features applied to a common representation or multiple analyses, one for each surface medium, with each extracting a similar set of features. The shared coding principles may facilitate the use of redundancy across media to reduce ambiguities in the locations and shapes of contours in the visual scene.

Vision has two goals: First, to determine the spatial layout of surfaces in the scene and second, to identify objects. In achieving these goals, it is likely that the visual system first encodes low-level features of the image. The nature of these low-level features, or coding primitives, of vision has been central to a wide range of research from Gibson's (1965) study of letter features to Julesz's (1981) textons.

Elementary Features

Treisman (Treisman, 1985; Treisman & Gelade, 1980; Treisman & Souther, 1985) has proposed a number of behavioral criteria that can be used to identify elementary features. For example, because elementary features are critical to the initial segregation of object surfaces, the visual system should be able to process these features simultaneously at all positions across the visual field. In particular, a stimulus that differs from a field of distractors by a single, elementary feature

should be distinguished effortlessly from the distractors, resulting in response times that are independent of the number of elements in the display. Several studies have shown that this property (labeled parallel processing or "pop-out") does occur with targets defined by certain visual features, including among others, a distinctive orientation, size, direction of motion, or color, or the presence of terminators or closure (Arguin & Cavanagh, 1988; Bergen & Julesz, 1983; Egeth, Jonides, & Wall, 1972; Nakayama & Silverman, 1986; Neisser, 1963; Treisman, 1985; Treisman & Gelade, 1980; Treisman & Gormican, 1988). The features identified by the parallel processing criterion generally are the same as those that mediate effortless texture segregation (Beck, 1982; Julesz, 1984; Treisman & Gelade, 1980) and as those that migrate independently to form illusory conjunctions (Treisman & Paterson, 1984; Treisman & Schmidt, 1982). These features are considered to belong to the set of primitives used by the visual system.

Physiological studies have shown that many units in the monkey visual cortex respond selectively to features that are similar to those identified by behavioral criteria in the visual search task. Examples are orientation and size (Hubel & Wiesel, 1968), motion (Movshon, Thompson, & Tolhurst, 1978), color (Zeki, 1973, 1978), binocular disparity (Bishop, 1973; Poggio & Fisher, 1977), line endings (von der Heydt, Peterhans, & Baumgartner, 1984), and curvature (Dobbins, Zucker, & Cynader, 1987). Such units may mediate the performance in behavioral tasks, perhaps by providing signals to higher level ensemble coding of stimulus properties.

Surface Media Versus Shape Features

We distinguish between two types of features: surface and shape (see Figure 1). Surface features, such as luminance,

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color, texture, motion, and binocular disparity define the regions of an image. Discontinuities in these features can separate figure from ground, giving the two-dimensional (2-D) contours of objects. For example, Julesz (1971) demonstrated that the contours of recognizable shapes can be defined solely by binocular disparity. We can think of each class of surface feature as a medium and the shape as the message (Treisman, 1988). In the case of a red square on an equiluminant yellow background, color is the surface medium in which the square is defined: The discontinuities in color trace the 2-D outline. The surface medium can be changed without changing the 2-D message: A square is still a square whether it is defined by color, texture, or luminance.

These different surface media are similar to the intrinsic images proposed by Barrow and Tenenbaum (1978). However, the intrinsic images they proposed were defined by high-level (distal) features, which include recovered scene properties such as reflectance and depth. In this study, we consider images specified only by low-level (proximal) features of luminance, color, binocular disparity, motion, and texture.

The contours traced by discontinuities in surface media can in turn be characterized by a different ensemble of features such as orientation, curvature, terminators, closure, and the relative lengths and sizes of edges, angles, and closed areas. These shape features are used to distinguish one object from

another and to identify each as a particular individual or member of a category. If a shape feature is changed, it will typically also change the shape it defines: A square with a curved, rotated, or shorter edge is no longer a square.

We can think of a figure as the conjunction of a set of shape features and the medium in which they are expressed. This conjunction is more fundamental than that of, say, color and motion, both of which are two surface media. A conjunction of surface media like color and motion requires the introduction of a third factor, a shape, along whose contours the discontinuities in the two-surface media are superimposed. Similarly, a conjunction of two shape features also requires the introduction of a third factor—the medium in which they are displayed.

Does the visual system exploit this basic difference between surface media and shape features? We suggest it does. A shape in a natural scene often differs from the background in several surface qualities, any or all of which may give only noisy or partial information about the location of image contours. For example, luminance on its own is not a reliable indicator of object contours because of the many shadow (luminance) borders that may fall across surfaces. Object contours are more reliably signaled by discontinuities in color, texture, relative motion, or binocular disparity. Because information about the contours of real objects is highly correlated across

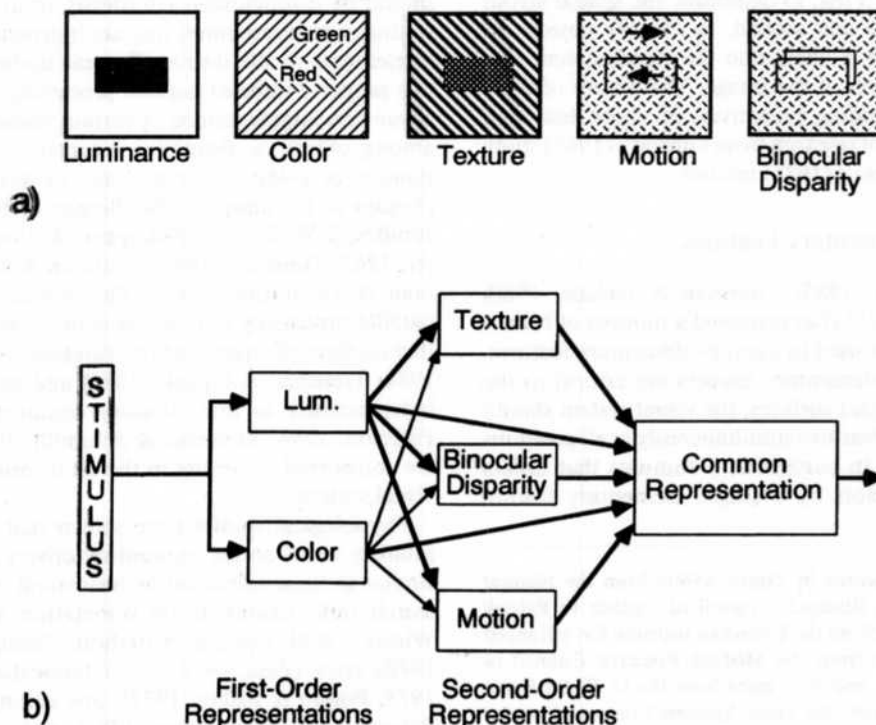


Figure 1. (a) The same shape may be expressed by discontinuities in different media. (b) The images defined in the different media are analyzed in separate representations (modules, Treisman, 1988, or pathways, Cavanagh, 1987, 1989) having two levels that correspond to the nature of the surface features that define the media: first-order, or point features of color and luminance, and second-order, or two-point features of texture, relative motion, and binocular disparity. (The discontinuities in the second-order media emerge from the analysis of shape features at the lower level. The analyses of all the media contribute to a common representation, equivalent to Treisman's [1988] map of locations.)

the different surface media, it should be advantageous to analyze each independently and then collate the information they provide. This cooperative localization of 2-D contours should be more accurate than that provided by the analysis of any one surface medium on its own. We suggest, then, that different surface media are analyzed in separate representations (modules, Treisman, 1988, or pathways, Cavanagh, 1987, 1988) and that within each of these representations, similar analyses of shape may be performed.

The images defined by the various surface media cannot all emerge at the same level in the visual system (Treisman, 1988). Within the five surface media that we have named, two are first-order or point features of the surface (color and luminance) and three are second-order or two-point features (texture, motion, and binocular disparity). The second-order features are constructed from spatial (texture), temporal (motion), or interocular (binocular disparity) structure in first-order features; for example, the binocular disparity between dots in a luminance image defines a stereoscopic image that has its own shapes with their own orientations and sizes. Figure 1 shows the relations we suggest between the three levels of representation. Similar coding principles may be involved in processing shapes defined in either first- or second-order media, reflecting general constraints of neural analysis. However, the scale and the level of processing are clearly different for first- and second-order media: The higher level surface media depend on and emerge from the shape features of the lower level image.

In some cases, the same nominal shape features can play a role on two levels. Thus, two textures may differ only in the orientation of the local lines that compose them (e.g., Nothdurft, 1985), while at the same time the boundary between them has its own orientation. Similarly, two textures may differ in the size of the dots they contain, whereas the regions defined by dots of different sizes may themselves also differ in their size. This hierarchical structure of primitive features or tokens was also noted by Marr (1982). In his model, grouping processes operated recursively at different scales on a single representation—the primal sketch—that combined all the primitive features. We suggest instead that similar grouping processes for boundary detection may be applied separately within a number of modules, each specialized for a different surface medium. The texture module or pathway of Figure 1 may actually comprise a number of separate submodules coding local orientation and spatial frequencies and possibly other local properties such as curvature versus angularity and the density of terminators (all candidate feature maps proposed by Treisman & Gormican, 1988).

Regions defined by discontinuities in the second-order media lead to global shape perception that is equivalent in most respects to that provided by first-order media—color or luminance (see Cavanagh, 1987, 1988). However, the visual system does have much lower spatial and temporal resolution for images defined in second-order media: 3 cycles deg^{-1} for disparity-defined (Tyler, 1974) or motion-defined (Nakayama & Tyler, 1981) images, for example, compared with 60 cycles deg^{-1} for luminance-defined images (Campbell & Green, 1965). Nevertheless, by restricting tests to images that can be resolved by the visual system, we can examine the ability to

encode shapes and to recover scene properties from 2-D images defined in each surface medium. Julesz (1971), for example, showed that we can perceive shapes defined only by binocular disparity in random-dot stereograms. More recent studies (Cavanagh, 1987) have made similar demonstrations for images defined by color, relative motion, and texture.

Physiological and Neuropsychological Evidence

The distinction between surface media and shape features is also suggested by the physiology of the visual system. Surface features such as color and motion appear to be extracted and analyzed independently, possibly in separate (Allman & Kaas, 1976; van Essen, 1985; van Essen & Maunsell, 1983; Zeki, 1973, 1978) or in compartmentalized (Livingstone & Hubel, 1988) regions, whereas shape features such as orientation may be coded within many, though not all, of the specialized regions (see De Yoe & Van Essen, 1988). The information defined in different surface media takes different routes through the visual system, and we have referred to these routes as visual or perceptual pathways (Cavanagh, 1988, 1989).

The reports of brain-damaged humans who show visual deficits specific to motion, color, or luminance also indicate that different surface media may be represented in separate regions of the visual cortex. Damage to one region may then affect only the analysis of one medium. For example, Zihl, von Cramon, and Mai (1983) reported a patient who is motion-blind. Botez (1975) reported the converse case of patients incapable of identifying objects unless they move. Damasio, Yamada, Damasio, Corbett, and McKee (1980) described case histories of cortically colorblind patients who only perceive in black and white. Conversely, Rovamo, Hyvärinen, and Hari (1982) described a luminance-blind patient. Reports of the selective loss of binocular depth vision (Benton & Hécaen, 1970; Carmon & Becholdt, 1969) have also been published. On the other hand, there is no obvious evidence of lesions of separate regions that analyze only orientation, or only size, or only curvature. It is possible that epileptic patients with micropsia, macropsia, or metamorphopsia (Walsh, 1978) may have deficits corresponding to losses in these functions, but it is difficult to make a strong case for this claim.

Elementary Shape Features of Five Surface Media

We have suggested that certain shape features may be analyzed separately for each of the surface media. Does the analysis for each medium rely on the same set of coding primitives such as size, orientation, terminators, and curvature that have been identified for luminance-defined stimuli? In this article, we report a test of parallel coding for two shape features—size and orientation—in each of five surface media.

Physiological experiments do not, as yet, unequivocally support orientation and size tuning for media other than luminance. Experiments have shown orientation and size tuning for color selective cells in area V1 of the monkey (Michael, 1978; Thorell, De Valois, & Albrecht, 1984) and area V4 (Zeki, 1978). More recently however, Lennie, Kraus-

kopf, and Sclar (1990) and Livingstone and Hubel (1988) failed to find orientation tuning in V1 cells that were primarily selective for color. So far, there have been no reports of selective tuning for orientation or size among cells responding to regions defined by relative motion (Hammond & MacKay, 1977; Hammond & Smith, 1982), binocular disparity (Poggio, Motter, Squatrito, & Trotter, 1985), or texture (Nothdurft & Li, 1985). There are reports of units in area MT that are selective for the direction of motion of bars defined by texture (Olavarria, De Yoe, Knierim, & Van Essen, 1988) and by relative motion (Albright, 1987). However, Movshon, Adelson, Gizzi, and Newsome (1985), by using compound grating stimuli, have shown that directional selectivity may occur in area MT without selectivity for the orientation of the stimuli. If orientation selectivity for second-order media does exist in individual cells, it may occur in area V4. Research with second-order media is under way in this area in several laboratories at present.

Psychophysical results, on the other hand, have consistently shown tilt aftereffects for all media tested: for stimuli defined only by color differences (Elsner, 1978; Flanagan, Cavanagh, & Favreau, 1989) and by differences in texture, movement, and binocular disparity (Cavanagh, 1989; Tyler, 1975). Such results suggest that orientation processing does occur at some level for these surface media. Similarly, size aftereffects have been observed for stimuli defined by color (Favreau & Cavanagh, 1981) and binocular disparity (Tyler, 1975).

In the present experiment, we used a visual search paradigm to evaluate the shape features available in five different surface media. The stimuli (both targets and distractors) were defined in turn by discontinuities in each of the media: luminance, color, texture, movement, or binocular disparity. The targets differed from the distractors in one of two shape features: size or orientation. The two values of each feature were selected to be highly discriminable so that processing would not be serial simply because the features were too similar (Treisman & Gormican, 1988). The number of stimuli presented on any trial varied from one to six, and on half of the trials, one of the stimuli was the target. We analyzed the search rate for these displays, that is, the increase with each additional distractor in the time required to detect a target. It was assumed that whenever the slope of the function relating search time to the number of items was not significantly greater than zero on positive trials, the distinction between the target and distractors was processed in parallel within a given surface medium and was thus available as a privileged or elementary feature in early processing (Treisman & Gelade, 1980; Treisman & Souther, 1985; Treisman, Sykes, & Gelade, 1977). We also investigated, for all five surface media and for both shape features, whether there were any search asymmetries (Treisman & Souther, 1985), the search rate being dependent on which value of the relevant feature (e.g., vertical or oblique orientation) defined the target.

Experiment 1

Method

Subjects. Eight observers (4 men and 4 women; average age = 28 years) took part in the experiment. All were right-handed, had normal

or corrected sight and normal color vision, and were able to see depth in random-dot stereograms.

Stimuli. The experiment was controlled by a Grinnell graphics system. The stimuli were displayed on a Conrac 5411 color video monitor.

The two stimuli used for orientation discrimination were solid rectangles of $1.5^\circ \times 0.5^\circ$ of visual angle, oriented either vertically or at 45° with their top to the right. The two stimuli used for size discriminations were filled disks subtending either 1° or 1.5° of visual angle.

The stimulus display subtended 8° of visual angle at a viewing distance of 1.93 m. Its average luminance was 26 cd m^{-2} . With the exception of the color and binocular disparity conditions, the display was at equal energy white, CIE (Commission Internationale d'Éclairage) x and y coordinates 0.333, 0.333. Except where stated otherwise, the target and distractors were filled with a random texture of contiguous dots. Each dot was $1/32$ of a degree square and was randomly chosen to be light or dark (half light, half dark). The contrast between the light and dark dots was 75%. The one to six stimuli that made up a given display were distributed randomly within a set of 18 possible locations situated at the intersections of three concentric circles (radius of 1° , 2° , and 3° of visual angle) and six equally spaced radii with the constraint that no two stimuli could be on adjacent intersections.

In the luminance condition, the Michelson contrast between the mean luminance of the stimuli and that of the background was 20%, with the stimuli (targets and distractors) brighter than the background. In the color condition, the stimuli were red on a green background. The red and green were produced by the red and green phosphors of the monitor and had CIE x and y coordinates of 0.596, 0.346 and 0.293, 0.604, respectively. The two colors were set to equiluminance in a separate task in which the observers adjusted both colors so that a subjective contour, whose inducing components were red on a green background, disappeared (Cavanagh, Shioiri, & MacLeod, 1987). The stimuli in the color condition were viewed monocularly with the dominant eye to avoid stereoscopy (Vos, 1960). In addition, we determined that both the random texture filling the background and the stimuli effectively masked residual luminance-based information with a luminance contrast of up to 10%. The texture-defined stimuli were filled with the random-dot texture described in the previous paragraph, whereas the background was of a uniform gray of the same mean luminance as the texture. There is, of course, an infinite variety of textures that might be chosen to produce texture-defined stimuli. We chose two textures, uniform versus random, that were highly discriminable. In the motion condition, the stimuli were filled with static texture, and the otherwise identical background texture moved at a speed of 2° s^{-1} to the left or right. The direction of motion was reversed on each trial in order to avoid motion aftereffects. Finally, disparity-defined stimuli were random-dot stereograms (we used the same random-dot textures described earlier) presented as red/green anaglyphs with the red and green images produced by the red and green phosphors, respectively, of the monitor. The stimuli (targets and distractors) had a disparity of 0.0° of visual angle and appeared in front of the random-dot background that had an uncrossed disparity of 0.095° . This disparity generated an apparent depth of about 10 cm between the stimuli and the background.

Between trials the display was filled with the same random texture described earlier, except that its contrast here was 25%. A fixation bull's-eye subtending $0.5^\circ \times 0.5^\circ$ was present in the center of the screen at all times.

Procedure. The experiment was run in a series of 20 blocks comprising 108 trials each. There were 10 blocks of trials for size discriminations and 2 for each of the five surface media, one block with the large disk serving as the target and small disks as the distractors and another block with the small disk as the target and large disks as the distractors. There were 10 similarly defined blocks

for the orientation discriminations. At the beginning of a block of trials, the subject was shown the target and distractor stimuli for that block. Blocks were run in a random order for each observer and any number of blocks could be run on the same day. Within a block of trials, the number of stimuli displayed varied randomly from one to six, and on half the trials the target was present. There were nine trials for each Set Size \times Trial Type (positive or negative) combination.

Subjects initiated a trial by tilting the response lever. A warning tone then sounded and was followed by a 500-ms delay after which the stimulus display was presented. Subjects responded to the presence or absence of a target by pushing the lever to the right (present) or left (absent) with the right hand. The stimuli remained on the screen until the subject responded or until a delay of 3 s had elapsed. If no response was made during this delay, the trial was counted as an error. Subjects were instructed to respond as rapidly as possible while avoiding errors. A double warning tone sounded after an incorrect response.

Results

Linear regression analyses and linear component analyses of the correct response times as a function of the number of stimuli displayed were performed on the untransformed data, separately for the two feature dimensions of size and orientation. Each experimental design involved the effects of four variables: surface medium (luminance, color, texture, motion,

or binocular disparity); target type (vertical or oblique for orientation, and large or small for size); target present or absent; and number of stimuli (one through six).

Mean response times for correct responses averaged across observers are shown in Figures 2 and 3. Tables 1 and 2 show the results from the linear regression and linear component analyses. The linear component analysis was used to determine the significance of the regression coefficients.

Error rates were quite low throughout all conditions and averaged 2.23% overall (Tables 1 & 2).

Orientation discrimination. Mean response times as a function of number of stimuli for orientation discriminations are shown in Figure 2.

Planned analyses of the search functions relating response times to the number of stimuli displayed were performed with linear component analyses. With the oblique targets (Table 1), no search rate was significantly greater than zero except (a) on positive trials, with stimuli defined in binocular disparity, and (b) on negative trials, with stimuli defined by relative motion. In the case of relative motion, the linear regression equation for negative trials indicates a negative slope, whereas the regression function for positive trials with binocular disparity stimuli indicates a positive slope.

With vertical targets (see Table 1), the results were very different. With only three exceptions, all the search functions were significantly greater than zero. The exceptions occurred

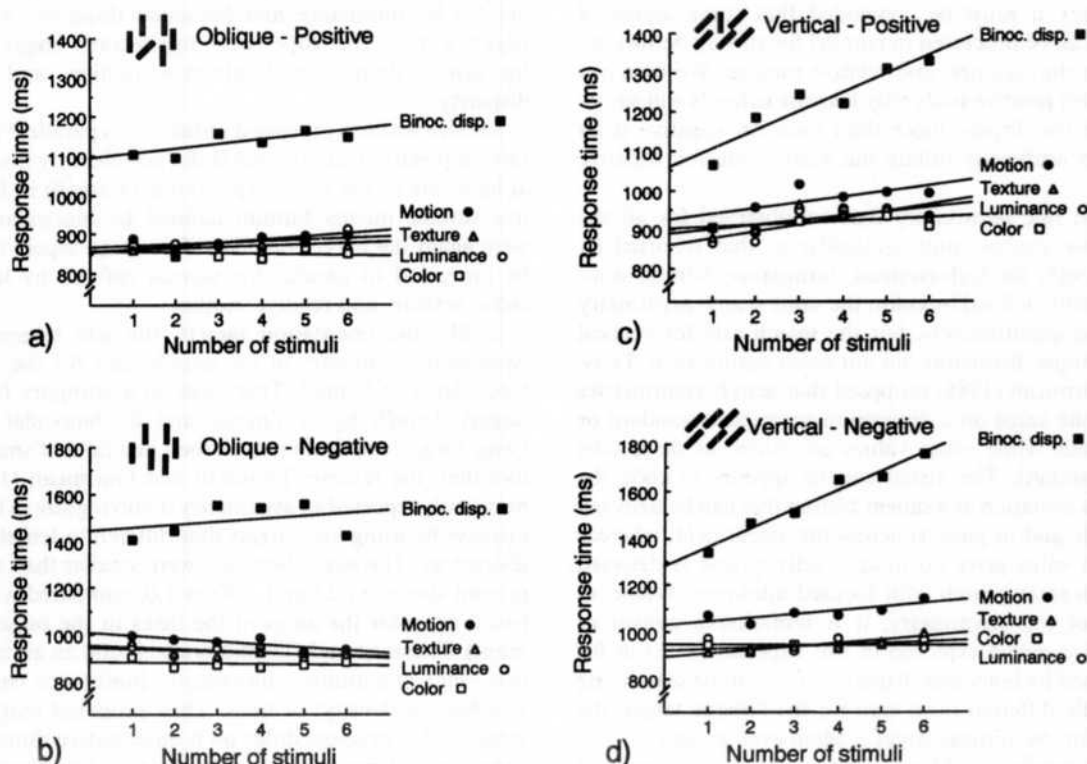


Figure 2. Mean response times as a function of the number of stimuli for (a) positive trials and (b) negative trials, in which the target is an oblique bar and distractors are vertical bars; mean response times as a function of the number of stimuli for (c) positive trials and (d) negative trials, in which the target is a vertical bar and distractors are oblique bars. (Regression lines are shown for each surface medium.)

Table 1
Intercept, Slope (in ms item⁻¹), and Error Rate (in percentage) for the Number of Stimuli Factors in the Orientation Task

Surface medium	Positive trials			Negative trials		
	Intercept	Slope	Errors	Intercept	Slope	Errors
Oblique target among vertical distractors						
Luminance	853	7.8	2.3	943	-5.8	0.9
Color	856	-1.9	2.1	883	-2.8	0.7
Texture	856	3.3	1.6	952	-7.5	1.9
Motion	866	3.6	2.3	952	-7.5*	0.9
Binocular disparity	1092	11.4*	2.3	1442	11.9	2.3
Vertical target among oblique distractors						
Luminance	858	17.6**	2.1	948	-0.9	2.1
Color	900	4.9	1.6	921	5.9	1.0
Texture	888	10.8*	1.6	893	14.1*	0.9
Motion	922	14.6**	1.9	1029	15.1**	1.6
Binocular disparity	1058	47.4**	4.6	1279	80.6**	3.0

Note. $df = 1, 35$.

* $p < .05$. ** $p < .01$.

for luminance-defined stimuli on negative trials and for stimuli defined in color on both positive and negative trials.

Are orientation features processed serially or in parallel? Our data show that the answer depends on which stimulus was the target and which the distractor. However, because the search rate on positive trials was never significantly greater than zero for oblique targets (except when defined by binocular disparity), it must be concluded that some aspect of orientation can be processed in parallel for stimuli defined by luminance, color, texture, and relative motion. We base our conclusions on positive trials only because subjects will sometimes search the display more than once on negative trials and this can artificially inflate the search rate for negative responses.

The search rate asymmetry that we observed for all the surface media, except color, is similar to that reported by Treisman (1985) for high-contrast, luminance-defined stimuli. With stimuli defined by color, the same search asymmetry was observed quantitatively, but the search rate for vertical targets in oblique distractors did not reach significance. Treisman and Gormican (1988) proposed that search asymmetries arise when one value on a dimension serves as a standard or reference value while other values are coded as deviations from the standard. The visual system appears to code the presence of a deviation as a salient feature that can be detected automatically and in parallel across the visual field, whereas the standard value gives no unique activity and is detected only through serial search with focused attention. Whatever the source of this asymmetry, it is remarkably consistent across the five media explored in this experiment. Even for stimuli defined by binocular disparity in which the search rate is significantly different from zero for the oblique target, the search rate for the vertical target is again even greater.

Size discrimination. Mean response times as a function of number of stimuli for size discriminations are shown in Figure 3.

Planned analyses of the search functions relating response times to the number of stimuli displayed were performed with linear component analyses. With the large target presented

among small distractors (Table 2), the slopes on the positive trials were significantly larger than zero only for the relative motion and binocular disparity media. On negative trials, however, all media, except texture, gave slopes that were significantly greater than zero. With the small target presented among large distractors (see Table 2), the slopes on positive trials were significantly greater than zero only for stimuli defined by luminance and binocular disparity, whereas on negative trials, the slopes were significantly larger than zero for stimuli defined by luminance, motion, and binocular disparity.

Are size features processed serially or in parallel? The search rate on positive trials did not differ significantly from zero for at least one of the target types (large or small) in four of the five surface media. Stimuli defined by binocular disparity were again the exception. Therefore some aspect of size can be processed in parallel for stimuli defined by luminance, color, texture, and relative motion.

Unlike the orientation targets, the size targets gave no consistent asymmetry in the search rates for the two target types, large and small. There was an asymmetry for the size targets defined by luminance and by binocular disparity: Large targets were more easily seen in a field of small distractors than the reverse. Treisman and Gormican (1988) have previously reported an asymmetry involving size in luminance displays by using line targets that differed in length from the distractors. The size differences were smaller than that of the present stimuli (1.23 and 1.60 to 1.0, compared with a 2.25-to-1.0 ratio for the areas of the disks in the present experiment). Treisman and Gormican also found an asymmetry for two other quantitative dimensions, luminance contrast and number (or density) of lines. They proposed that when the target and distractors differ on a quantitative dimension, the stimulus that produces more activation (the larger disks in our experiment) will be coded in the same way as a deviation from the standard or reference value on a qualitative dimension. This follows from the idea that the presence of added responses (signaling either an additional feature or an increase in a shared feature) is easier to detect than their absence.

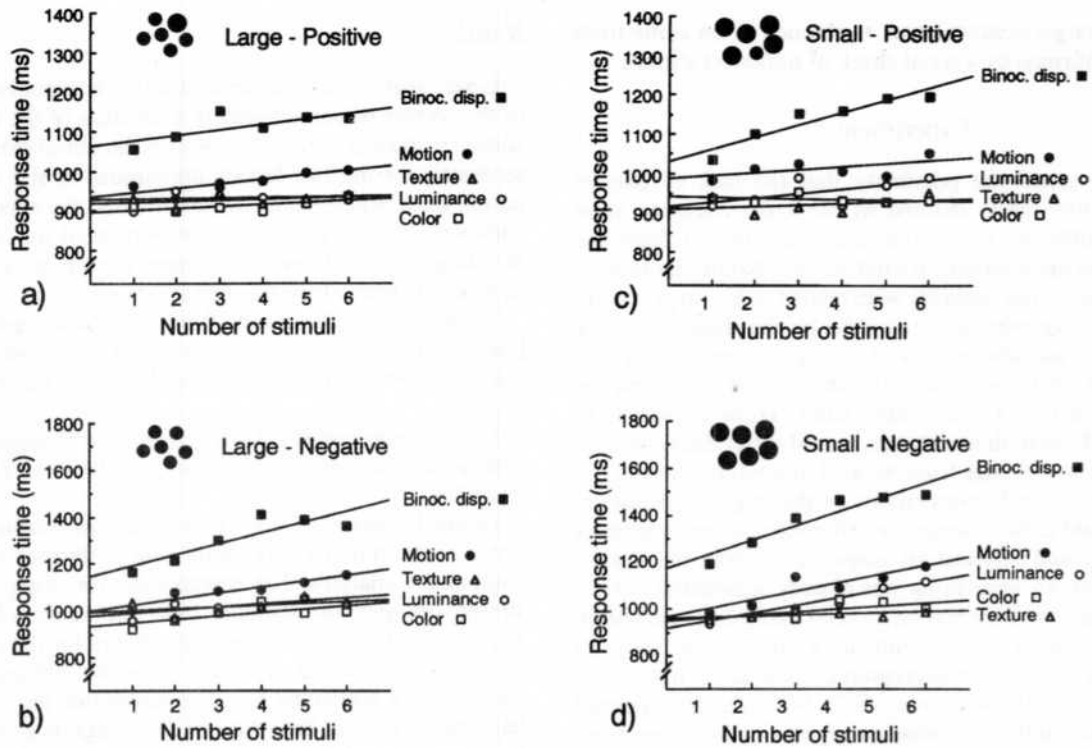


Figure 3. Mean response times as a function of the number of stimuli for (a) positive trials and (b) negative trials, in which the target is a large disk and distractors are small disks; mean response times as a function of the number of stimuli for (c) positive trials and (d) negative trials, in which the target is a small disk and distractors are large disks. (Regression lines are shown for each surface medium.)

Comparison of positive and negative slopes. When search is serial and self-terminating, the slope on negative trials is expected to be twice the slope of positive trials. The data approximated this ratio for the conditions with significant slopes on positive trials; the mean slopes were 31.8 and 18.8 ms per item for negative and positive slopes respectively. For the remaining conditions, the results differed for the two types of targets. With targets defined by size, the negative slopes

were on average much steeper than the positive slopes (14.9 ms compared with 3.1 ms per item), whereas with targets defined by orientation, the reverse was the case (-3.5 ms compared with 3.5 ms per item). This suggests a possible difference in the coding of orientation and size: The homogeneity of dense displays may be salient for stimuli defined by orientation, allowing a global response to the display as a whole, whereas when size is the relevant dimension, only the

Table 2
Intercept, Slope (in $ms\ item^{-1}$), and Error Rate (in percentage) for the Number of Stimuli Factors in the Size Task

Surface medium	Positive trials			Negative trials		
	Intercept	Slope	Errors	Intercept	Slope	Errors
Large target among small distractors						
Luminance	928	1.4	3.2	973	13.0*	1.9
Color	893	4.9	2.5	929	14.9*	1.9
Texture	917	2.8	3.5	988	8.3	0.9
Motion	932	11.4*	6.2	995	26.2**	2.1
Binocular disparity	1062	14.2**	2.8	1144	46.2**	1.4
Small target among large distractors						
Luminance	916	11.1*	2.3	925	32.8**	0.9
Color	943	-1.7	2.1	960	12.2	2.1
Texture	911	3.7	1.6	968	4.3	1.9
Motion	987	7.5	2.3	973	37.5**	0.9
Binocular disparity	1032	30.9**	2.3	1181	60.2**	2.3

Note. $df = 1, 35$.

* $p < .05$. ** $p < .01$.

discrepant target is salient and its absence is, on some trials at least, confirmed by a serial check of nontarget stimuli.

Experiment 2

We next tested the possibility that the lack of parallel processing for stimuli defined by binocular disparity arose from the difficulty in discriminating the targets from the distractors in this medium. We did not feel that the anomalous results for binocular disparity were related to the three-dimensional (3-D) representation invoked by the display because the motion task also produced strong impressions of 3-D surfaces but gave results quite similar to those of luminance, color, and texture. On the other hand, Treisman and Gormican (1988) have shown that decreased target discriminability can lead to a change from parallel to serial processing.

To increase the discriminability of the targets and distractors, we could either change the differences in orientation or size or we could increase the disparity defining the shapes. The disparity we were using was already substantial (0.095° of visual angle) and increasing it could easily decrease visibility, which reaches a maximum at a fairly small value of disparity for random-dot stereograms (about 0.2° , Grabowska, 1983; 0.13° to 0.25° , Richards, 1977). We therefore increased the orientation difference between targets and distractors from 45° to 90° (vertical vs. horizontal bars) in the orientation task and the size difference from 2.25:1 to 4:1 (in terms of area) in the size task and repeated the binocular disparity conditions of the first experiment.

Method

Subjects. Five experienced psychophysical observers (3 men and 2 women; average age = 30 years) took part in the experiment. All were right-handed, had normal or corrected sight, and were able to see depth in random-dot stereograms.

Stimuli. The two stimuli used for orientation discrimination were solid rectangles of $1.5^\circ \times 0.5^\circ$ of visual angle, oriented either vertically or horizontally. The two stimuli used for size discriminations were filled disks subtending either 1° or 2° of visual angle.

In all other respects the displays were identical to those of the first experiment in the binocular disparity conditions.

Procedure. The procedure was identical to that of the previous experiment with the exception that, due to the demise of both our joystick and its manufacturer, responses were made by subjects sliding a computer mouse left or right rather than using a joystick lever.

Results

Linear regression analyses and linear component analyses of the correct response times as a function of the number of stimuli displayed were performed on the untransformed data, separately for the two feature dimensions of size and orientation. Each experimental design involved the effects of three variables: target type (vertical or horizontal for orientation, and large or small for size); target present or absent; and number of stimuli (one through six).

Table 3 shows the results from the linear regression and linear component analyses. The linear component analysis was used to determine the significance of the regression coefficients.

Error rates averaged 6.2% overall (Table 3), higher than the average for the binocular disparity conditions in Experiment 1 (2.6%).

Planned analyses of the search functions relating response times to the number of stimuli were performed with linear component analyses. The search rates for disparity-defined stimuli dropped substantially from the values observed in Experiment 1. The search rate asymmetry for the orientation task was maintained, although now the oblique bar was replaced by a horizontal bar. The search rate for a horizontal bar among vertical bars did not reach significance, whereas that for a vertical bar among horizontal bars did (on positive trials only). Following the logic of Treisman and Gormican (1988), this result implies that the vertical orientation serves as a reference but the horizontal does not. For the size task, no search rate differed significantly from zero and there was no significant search rate asymmetry for the large versus small targets.

Are size and orientation features processed serially or in parallel for these more discriminable stimuli? The search rates in this second experiment are lower than those of the first, often by a factor of two or more. In particular, the search rates on positive trials in this experiment did not differ significantly from zero for at least one of the target types for each feature (horizontal bars in the orientation task and both small and large disks in the size task). Therefore some aspects of both orientation and size can be processed in parallel for stimuli defined by binocular disparity as long as the targets and distractors are sufficiently discriminable.

The intercepts of the response functions for the binocular disparity tests also decreased compared with those of Experi-

Table 3
Intercept (in ms), Slope (in ms item⁻¹), and Error Rate (Percentages) for the Number of Stimuli Factors in the Size and Orientation Tasks for Binocular Disparity Displays, Experiment 2

Condition	Positive trials			Negative trials		
	Intercept	Slope	Errors	Intercept	Slope	Errors
Horizontal target among vertical distractors	789	5.8	10.0	1017	-11.0	5.6
Vertical target among horizontal distractors	755	24.4*	7.0	928	20.9	5.7
Large target among small distractors	632	6.4	8.9	781	-1.4	4.8
Small target among large distractors	751	0.9	4.3	797	9.1	4.3

Note. $df = 1, 20$.

* $p < .01$.

ment 1. However, we changed both the subjects and the response apparatus (the response lever used in Experiment 1 was damaged and had to be replaced with a mouse in Experiment 2), so we cannot attribute the change in intercepts unequivocally to the higher discriminability of the stimuli. In particular, the higher error rate in this second experiment (despite the increase in stimulus discriminability) indicates that there was some shift in the response criterion and this may account for part of the decrease in average response time. To get an estimate of the difference between the intercepts for luminance tests and binocular disparity tests when both were evaluated with the same stimuli, subjects, and apparatus, we ran an additional condition: The 5 subjects of the second experiment were run in the orientation task with horizontal targets in vertical distractors by using luminance-defined stimuli (generated as in Experiment 1) and the new response key. The intercept was 529.2 ms for the positive trials, 260.5 ms less than the comparable intercept for the disparity-defined test in this second experiment (see Table 3). This is similar to the difference of 239.2 ms between the luminance- and disparity-defined tests for the oblique-vertical conditions of the first experiment (see Table 1). The difference in intercepts between the first and second experiments therefore appears to be attributable in large part to subject and equipment factors.

General Discussion

Parallel Coding of Orientation and Size

The main result in Experiment 1 is that for the surface media of luminance, color, texture, and relative movement, search for targets defined by orientation or size could be performed in parallel. That is, for at least one of the two targets defined in those surface media, the slope of the function relating the response time to the number of stimuli did not differ significantly from zero on positive trials. If we assume that parallel processing of a given feature implies its early encoding in the visual system by specialized detectors (Treisman, 1985; Treisman & Gelade, 1980; Treisman & Souther, 1985), we may conclude that, for these four surface media, the extraction of local structure involves the shape features of orientation and size.

We have chosen the criterion of a nonsignificant slope in the positive trials as evidence for parallel processing. In effect, we have identified the conditions in which there was significant serial processing and assumed by default that the processing in the remainder was parallel. However, the dichotomy between parallel and serial processing may be an oversimplification if attention can in fact be focused, more or less narrowly, on one item or on pairs, triplets, or larger groups (Eriksen & Hoffman, 1972; Treisman, 1982; Treisman & Gormican, 1988). There may instead be a continuum of attention allocation determined by the discriminability of the target from the distractors. Treisman and Souther (1985) showed that decreased target discriminability can lead to a change from parallel to serial processing. If parallel search depends on the detection of activity in separate classes of

detectors coding the target but not the distractors, it should be possible only when the target activates a population of detectors that is clearly separable from those that respond to the distractors. When the two produce overlapping distributions of activity, attention may be narrowed to process subgroups of items or single items at a time (Treisman & Gormican, 1988). Search functions with shallow slopes would imply a rapid scan with a broad aperture to the "window" of attention, whereas steep slopes would imply a need for more narrowly focused attention, restricted at the limit to one item at a time.

In Experiment 1, even the smallest slopes in the positive trials averaged more than zero (a mean of about 4.0 ms item⁻¹). However, these very low search rates suggest processing that is either parallel (with slight increases in uncertainty or interitem interference causing slightly longer latencies with large displays) or serial across large groups of items. They contrast markedly with the conditions giving substantial slopes, suggesting much more severe attention limits (e.g., the vertical targets in oblique distractors or the binocular tests in the first experiment).

The second experiment, using more discriminable stimuli, found parallel processing for size and orientation discriminations with disparity-defined stimuli. It is likely, therefore, that the significant search rates with disparity-defined stimuli in Experiment 1 resulted from poor stimulus discriminability. In their study of size discriminations, Treisman and Gormican (1988) also found apparently serial processing for luminance-defined targets differing in length, with slower search rates for a size ratio of 1.23 to 1 than for size ratio of 1.60 to 1. Although the size and orientation differences in Experiment 1 were larger than those of Treisman and Gormican's, they apparently approached the limits of discriminability when the stimuli were presented as stereograms. In Experiment 2, the target-distractor differences were increased to compensate for the lower spatial resolution of the binocular disparity medium, and parallel processing resulted. Our conclusion is that size and orientation are shape features for disparity-defined stimuli, as well as for the other four surface media, but that the specificity of orientation and size features for binocular disparity-defined shapes may be less sharply tuned than is the case in the other surface media.

Search Asymmetry

An interesting aspect in our results is the search asymmetry observed for discriminations of orientation in all the surface media studied. With the exception of color-defined stimuli, search was parallel when the target was an oblique shown among vertical distractors (or in Experiment 2, horizontal among vertical for disparity-defined stimuli), whereas it appeared to be serial when the target was a vertical presented among oblique distractors. With stimuli defined by color, the same search asymmetry was observed quantitatively, but the search rate for vertical targets in oblique distractors did not reach significance. This asymmetry between search for vertical and oblique targets is similar to that reported by Treisman (1985) and Treisman and Gormican (1988) with high-contrast, luminance-defined stimuli. Models that may account

for such an asymmetry have been described by Treisman and Gormican.

Intercept Effects and Surface Segregation

Another point worth noting is that the slopes of the search times as a function of the number of items can be flat even when the intercepts are very high (see also Treisman, Cavanagh, Fischer, Ramachandran, & von der Heydt, 1990). All the present search tasks gave much longer response times than those found by Treisman and Gormican (1988) for stimuli defined by luminance with high contrast black lines against a white background, where the intercepts averaged between 400 and 600 ms. Some portion of the higher intercept may be attributable to the response mode in our experiment: a left or right tilt of a lever rather than the more typical button press with the left or right index finger. Nevertheless, even within the present experiments, the intercepts varied considerably: They were much higher for stimuli defined by binocular disparity than for stimuli defined by other attributes. Tables 1-3 show the mean intercepts for positive and negative trials with size and orientation targets separately for each medium. There was little difference between color-, luminance-, texture-, and motion-defined stimuli, but stimuli defined by stereopsis were processed much more slowly.

We could account for these different patterns of search performance by assuming that two separate factors contribute additively (Sternberg, 1969) to response time in the search tasks: (a) the ease of segregating the figures from ground and detecting the shapes within each medium, and (b) the discriminability between the features of the shapes defining the target and the distractors within each medium. The former may contribute a constant amount to the search time—a small component for high contrast luminance stimuli and a very large component for binocular disparity, with intermediate amounts for the other media (including the small luminance contrast masked by random-dot texture used in the present luminance tasks). In addition, the reduced resolution available in surface media other than luminance may make the discrimination between target and distractors more difficult, thus inducing serial search rather than parallel detection for some of the stimuli.

Do our results generalize to other stimuli? Given the range of conditions over which we found the same results, it is not unreasonable to assume that our results generalize very widely to other instances (other colors, other textures, etc.) within the surface media that we tested. The results of Experiment 2 suggest that rapid search rates for orientation and size discrimination can be observed in each of the media as long as the targets and distractors are sufficiently discriminable.

Single or Multiple Coding of Shape Features

The similarity of the results across the luminance, color, texture, motion, and disparity (in Experiment 2) media is striking. The asymmetry of search in the orientation discriminations tasks is in the same direction for all of the surface media. Codes for orientation and for size appear to be avail-

able not only for stimuli defined by luminance but also for stimuli defined by color, texture, relative motion, and binocular disparity.

There are two possible accounts of these results: One is that the features tested in the visual search task—differences in size and in orientation—are coded separately but in a very similar way for shapes defined by luminance, color, texture, motion, and disparity boundaries. Another is that the features are coded in a final, common representation. The similarity of our results across media would be explained by the common analysis of size and orientation features in this high-level representation.

Evidence from tasks measuring aftereffects of selective adaptation favors the former interpretation, suggesting that orientation and size codes are indeed duplicated in the separate analyses of different surface media. Specifically, studies have shown that opposite tilt aftereffects can be induced simultaneously for color and luminance stimuli (Flanagan et al., 1989), as can opposite size aftereffects (Favreau & Cavanagh, 1981). These results and others involving tilt illusions (Cavanagh, 1989) require the duplication of size coding for at least the color and luminance media and of orientation coding for all five media. The inference is that the information that is taken from each medium to form the final interpretation of the visual scene consists of abstracted features of edges and shapes rather than the raw edges themselves.

Evidence from our visual search experiments does not resolve this issue directly but does make two points. First, we have demonstrated that size and orientation coding is available for each of these five media. At some level, size and orientation analysis must be performed on images defined by any of these media.

Second, there must be at least two (and perhaps as many as six) separate analyses of size and orientation features (Figure 4). We raised this possibility in the introduction when we suggested that there were different vocabularies of features for, on one hand, the shapes defined in second-order media like texture and, on the other hand, the local shapes of the luminance-defined elements that create the textures. These are clearly two different levels of coding. Figure 4 depicts three ways in which these different levels of coding might be involved in the visual search task. In the first two, shown in Figure 4a and 4b, the level of coding that mediates performance in the visual search task is the final, common representation that combines information from all media, thus explaining the similarity in our results across media. In Figure 4a, evidence from the different media about the location of discontinuities would be combined in a single representation and an analysis of shape features would operate at that level. Even in this case, however, there is at least one additional analysis of size and orientation features that precedes this final level. This is the early analysis of size and orientation in visual area V1 (Hubel & Wiesel, 1968) that responds to luminance-defined stimuli but not to higher order stimuli (Nothdurft & Li, 1985; Poggio et al., 1985; von der Heydt et al., 1984). In Figure 4b, on the other hand, the final representation is preceded by several separate analyses of size and orientation, as suggested by the aftereffect (Favreau & Cavanagh, 1981; Flanagan et al., 1989) and illusion data (Cava-

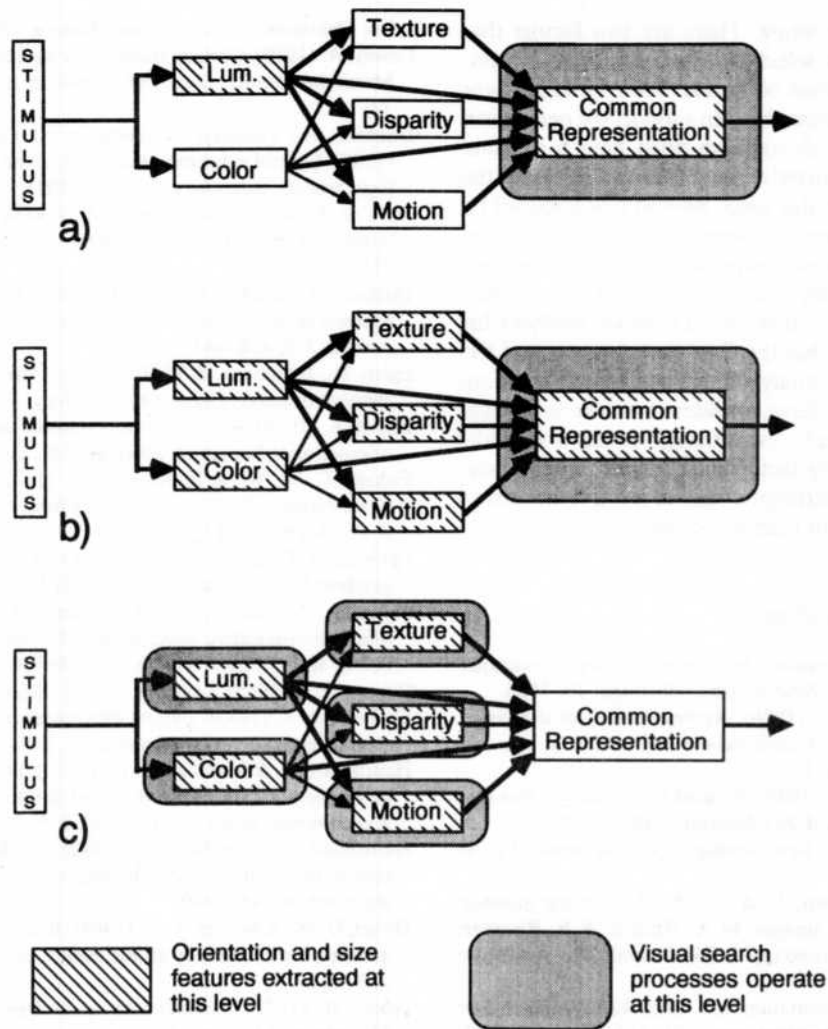


Figure 4. Possible arrangements of the extraction of size and orientation features (at locations filled with diagonal lines) and the processing that mediates visual search (at locations surrounded by larger gray box). (a) Only the shape features of size and orientation extracted at the level of the common representation mediate performance in the visual search tasks. Of the preceding, separate analyses of the different media, only that for luminance explicitly extracts size and orientation features. (b) Only the shape features of size and orientation extracted at the level of the common representation mediate performance in the visual search tasks. Size and orientation features are also extracted separately in the individual analysis of each medium preceding the common representation. (c) The shape features of size and orientation that mediate performance in the visual search tasks are those extracted separately for each medium.

nagh, 1989). In this case, however, these analyses do not mediate performance in the visual search task. Finally, visual search performance may be mediated by five similar but separate representations for the individual media, each with its own analysis of shape features (Figure 4c).

Our data here do not discriminate between visual search processes that rely on one common analysis (Figure 4a or 4b) or on five separate but similar shape analyses (Figure 4c). The possibility of multiple, independent analyses (at least, of more than two) in the visual search task will have to be examined in further experiments. However, we believe that the visual system may have developed a separate analysis of each me-

dium not only because of the neural economies this might confer (Barlow, 1986; Cowey, 1979) but also to exploit the advantages of cooperative localization of 2-D discontinuities across media. This would explain why the separate analyses all make use of similar vocabularies of shape features: a standard set of shape features would serve as a common code for exchanging, comparing, and combining images.

The five different media that we have tested do not necessarily form an exhaustive list. What we have chosen to call a medium is determined in a circular fashion by the stimulus properties that can be processed independently by the brain, just as what we call light is determined by the response

spectrum of our photoreceptors. There are two factors that limit what we can usefully select as a medium. First, discontinuities in the medium must be visible: They must produce a response in the visual system that can support the perception of 2-D shapes. Second, each medium must have a separate analysis at some level; otherwise we artificially increase the dimensionality of our stimulus space beyond that encoded by the visual system. Our present experiments have addressed only the question of response—whether or not there are size- and orientation-specific responses for the media we tested. We have not examined the question of separate analyses for each medium. It is likely that the final list of media and the pathways or modules that analyze them will extend to more than five. In particular, we have considered texture as a single medium in our experiments, even though it has a multidimensional nature involving factors such as size, orientation, and curvature. Future experiments may reveal a richer structure of individual media for different classes of texture.

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