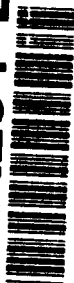


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13. ABSTRACT (Maximum 200 words)

Recent evidence indicates that the early stages in visual processing may be broken into several parallel streams that are specialized for the analysis of different visual attributes. A contour localization task showed that all attributes can contribute equally to border localization — no particular attribute dominated position decisions. A series of experiments on transparency perception showed that transparency is analyzed rapidly (within 60 msec) and influences early levels of visual processing. We have also investigated the early stages that lead from the initial 2-D representation to object recognition. Visual priming studies have been completed which suggest that object recognition begins, not with the construction of a 3-D model, but with a crude match of 2-D views to internal prototypes. Visual search studies have shown that some scene features may be rapidly suppressed. For example, shadows appear to be identified early and discounted in order to allow object contours to be processed. Finally, long-term practice in visual search tasks leads to learning of both object-centered and retinotopic properties of the stimuli.

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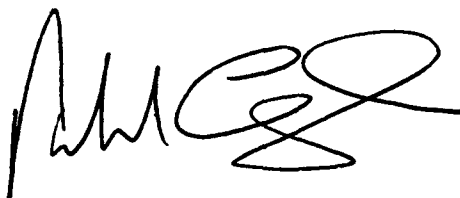
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Cooperativity and 3-D Representation

Patrick Cavanagh
Psychology Department
Harvard University
33 Kirkland Street
Cambridge, MA 02138



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Cooperativity and 3-D Representation

Objectives

Our work has concentrated on how 2-D information is built up from the parallel analysis of a set of visual attributes and how this information contacts memory in order to construct 3-D representations of the visual scene. We are interested in the coding of image contours and how they arise from the various attributes which can define contours. We have examined the decomposition of image values into object features (reflectance, orientation, 3D position) and illumination features (shadows, shading, highlights) and especially how the perception of transparency leads to the distribution of image values to two or more superimposed surfaces. Finally, we have studied the initial contact between the image contours and memory in recognition.

Progress Report

Several projects dealing with the contribution of early streams to a common representation have been completed during the grant period. These will be described first followed by the results in our visual search explorations of coding in early processing and finally by the priming results for the early 2-D match experiments.

1. Cross-media cooperation in contour localization. If different attributes such as color, motion, luminance, and texture are first analyzed independently, their representations must subsequently be recombined in some manner. In order to determine the nature of this recombination, we completed several studies using a vernier acuity task. Some studies have been published on vernier tasks for media other than luminance. In particular, Regan (1986) has reported that the alignment of motion-defined edges is as accurate as that for luminance-defined edges and Farell and Krauskopf (1989) make the same point for vernier alignment of low-pass, equiluminous, chromatic bars.

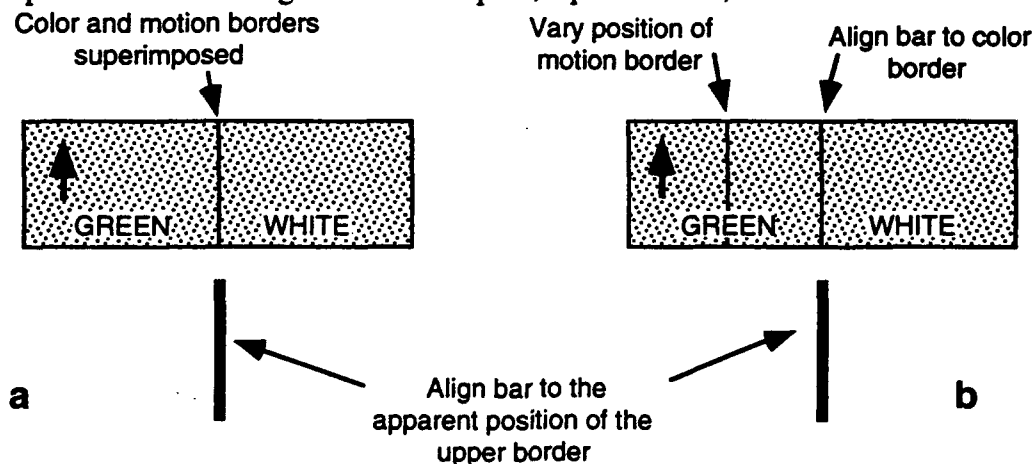


Fig. 6a. Vernier alignment task where the upper border is a discontinuity defined in one or several media (color and motion depicted here). b) Vernier alignment of one border in the presence of a second border defined in a different medium.

In the first experiment, a vertical border was presented in the upper field defined in by one attribute (e.g. green on the left, white on the right, both areas filled with a fine dynamic luminance texture) or several as shown in Figure 6a (e.g. green with texture moving up on the left, white with dynamic texture having no coherent motion on the right). The lower field was white with a fine, vertical, black line whose position was randomly offset relative to that of the upper border. Observers reported whether the lower line fell to the left or right of the upper border in forced choice task. The magnitude of the color, luminance, or texture discontinuity defining the border was adjusted to produce approximately equal precision of localization for each attribute when presented alone. The result of interest was the effect of defining the border by discontinuities in several attributes simultaneously (two or three at a time). The degree of improvement of localization (the JND of the psychometric function) indicated that all attributes tested (color, luminance, and texture) contributed equally to the improvement when they were paired. Moreover, the improvement was greater than could be expected from an independent localization of the discontinuities in each attribute followed by probability summation of the decisions comparing each of those locations to the test line below. These results indicated that some graded information from each attribute was being

combined before the localization decision was made.

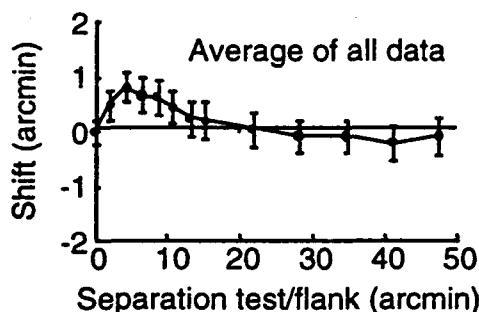


Fig. 7. Apparent shift of test line caused by the adjacent flanking line. The pattern was similar for all pairings of test and flanking attributes.

The next experiment demonstrated that this graded information was a profile of activity representing the discontinuity and that these profiles were summed into a common representation, independently of the attributes defining the discontinuities. Westheimer and his colleagues (eg, Badcock & Westheimer, 1985) had earlier shown that adjacent luminance contours interact, attracting or repelling each other depending

on their spacing. These shifts could be accurately modeled by summing the profiles of activity of cortical cells to each line. The peaks of these summed distributions shifted towards each other or away in a manner consistent with the psychophysical results. Assuming that each line's position was based on the peak of the profile of neural activity in response to the line, this result established that the two luminance contours could interact through a common, spatially extended representation. We extended these experiments to measure the interactions between contours defined by different attributes.

The displacement of the apparent border position was measured as a function of the position of the neighboring border defined by a different attribute (see Figure 6b, again after adjusting the magnitude of the border discontinuity in each attribute so that localization was equally precise when the border was presented in each attribute alone). The results (see Fig. 7 for the average position shift) showed that basically all contours interacted in a similar manner suggesting a common final representation for contours independent of the attribute that defines them. For example, a color contour was strongly attracted toward an adjacent luminance contour if the two were within 10 min of arc of each other. The reverse was also true, a luminance contour was attracted towards an adjacent color contour. This pattern of attraction (repulsion was much weaker) again suggests the summing of profiles of activity as originally proposed by Badcock and Westheimer (1985) but now the profiles originate from the analyses of different attributes and they must be summed in some attribute-invariant, final representation. These results challenge the models of Gregory (1979) and Grossberg and Mingolla (1985) that predict that luminance is a privileged signal for contours.

This work was presented at ARVO in 1991 and 1992 and manuscripts are being prepared for publication. Josée Rivest has returned to our lab this summer to work on these manuscripts and two additional experiments.

2. Early visual memory: persistence. With Dr. Satoshi Shioiri at ATR in Japan, we investigated the memory for spatial position provided by luminance and by relative motion (Shioiri & Cavanagh, 1992). The early visual memory that we tested is the decaying visible trace of the stimulus. A partial (4x4) matrix technique developed by DiLollo (1977) was used where the first partial set of elements precedes the second partial set by a short interval. One element is missing from the combined representation of the two partial matrices. Because of the large number of matrix positions (16 in our experiments), the missing element can only be identified if the image of the first partial matrix persists until the presentation of the second. The two are then effectively superimposed and the missing element "pops out". We found that pattern features defined by relative motion did exhibit visual persistence for durations similar to that for luminance-defined patterns. Although we had too little information to draw a final conclusion, it is possible that there is one site for visual persistence that follows the attribute-specific detectors and that is largely attribute independent.

3. Monocular depth cues. Our earlier work on size and tilt aftereffects (Cavanagh, 1989; Favreau & Cavanagh, 1981; Flanagan, Cavanagh & Favreau, 1990) gave no evidence of special primacy or privilege for luminance information other than the extra resolution it affords. The same conclusion also appears to hold for the analysis of 3-

D shape (Cavanagh, 1987, 1988). These results are in opposition to the claims of Livingstone and Hubel (1987) that several monocular depth cues are ineffective when presented in equiluminous, chromatic stimuli. However, the loss of depth in their stimuli was likely due to the fine detail in their figures which could only be clearly resolved (especially in the periphery) if luminance was present. At equiluminance, therefore, both the stimulus and the depth were difficult to see. In a continuation of these studies, Lee Zimmerman, Gordon Legge, and I evaluated the efficiency of perspective cues for surface

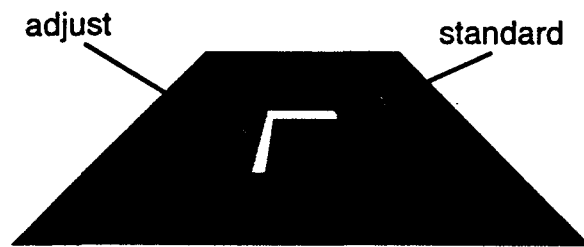


Fig. 8. Tests of perspective cues to slant. One bar was adjusted until it has the same apparent length as the standard

slant when a tilted plane is defined in luminance as compared to when it is defined in color (Zimmerman, Legge, & Cavanagh, submitted to *JOSA*).

Γ -shaped probes (Fig. 8) were placed on the tilted surface and the observer adjusted the relative lengths of the lines until they appeared to have equal length. We assumed that the greater the perceived slant of the plane,

the shorter the setting of the adjustment line (foreshortening). Several different simulated slants were presented by changing the shape of the trapezoid and the perceived slant was determined from the amount of foreshortening in the adjustment. The judgments of slant impression were accurate to within 3% of the veridical value in both the equiluminous case and the luminance-defined case. These results imply that the extraction of these perspective cues operates at a level following the integration of the different attributes into a common representation.

4. Transparency. Takeo Watanabe and I have examined the surface decomposition accompanying transparency perception. We show that the surface

Valid for luminance transparency

Invalid for luminance transparency



Fig. 9. Transparency of stimuli evaluated using a recognition task. Recognition is easier for the stimuli on the left than for those on the right.

decomposition occurs rapidly, it affects even early stages of visual processing, and it involves attributes such as texture and motion as well as color and brightness (see Watanabe & Cavanagh, 1993a, for a review). In the first experiment (Watanabe & Cavanagh, 1992b), we developed and validated a measure of functional transparency that reduces the variability of traditional subjective report techniques. The method is a reaction-time version of a technique originally described by de Weert (1986). Using four overlapped digits (Figure 9) and varying the luminance of the overlap region we found that faster reaction times are obtained for stimuli with luminances valid for transparency than for stimuli with invalid luminances (while holding border contrast magnitudes constant). This advantage became apparent with as little as 60 msec of exposure of the digits. Because the technique requires only a simple recognition response by the subject, it has been adopted in at least two alert primate labs as a method of assessing transparency perception in animals.

In a second experiment (Watanabe, Zimmerman, & Cavanagh, 1992), the separation of overlying, orthogonal grids due to transparency was found to influence the strength of the McCollough effect, an effect attributed to early cortical processing. Following adaptation to traditional vertical red and horizontal green gratings, observers were shown overlapping horizontal and vertical grids which could either look like overlapping sets of gratings if they were seen as transparent or as a checkerboard pattern if transparency was not seen. The orientation-contingent color aftereffect was significantly larger when the grids appeared to be transparent.

In a third experiment (Watanabe, & Cavanagh, 1991), we showed that transparency involves not only surface color or brightness but also texture and motion. When a transparent surface appears to extend over areas that are physically identical to the background, we found that the texture and motion qualities of the transparent overlay also appear to fill the illusory overlying region.

In two other experiments, we examined the nature of contours and contour junctions involved in transparency. First (Watanabe & Cavanagh, 1992a), we discovered that a transparent overlay can capture some of the features of surfaces visible beneath it. Typically, transparency involves seeing two superimposed surfaces at different depths. However, if the contours of the further surface (as specified by binocular disparity) are defined by equiluminous color or are illusory, the colored or illusory figures appear to lie on the front, transparent surface (note that in the latter case, the inducing figure was still perceived to lie in the rear plane). The ability to appreciate a depth separation between transparent surfaces may therefore require the presence of explicit luminance contours.

In another experiment (Watanabe & Cavanagh, 1993b), we discovered that a T-junction is not an invariant cue to occlusion but can signal transparency. Typically, transparent surfaces are signaled by X-junctions where the contour of the overlying transparent surface crosses over contours of the surface below. There is, however, a special case where a surface can return the same amount of light to the observer whether viewed directly or viewed through a overlying, transparent surface (ie, when the light reflected from the transparent surface equals the light loss in transmission through it). In this case there no border is visible between the transparent surface and the underlying surface. A typical X-junction in this case becomes a T-junction and several demonstration images showed that observers can see these instances as transparent. Transparency is not always the initial impression but it appears always to be a possible percept.

5. Visual search: level of representation. Recent studies of visual search have demonstrated rapid processing for intermediate- to high-level attributes such as 3-D surfaces (He & Nakayama, 1992), orientation of 3-D objects (Enns & Rensink, 1991; 1990b), shadows (Rensink & Cavanagh, 1993), and stimulus familiarity (Wang & Cavanagh, 1992). These studies suggest that the visual system can process different levels of image representation during rapid pattern discrimination. Satoru Suzuki and I (Suzuki & Cavanagh, 1992) examined the case where visual search had a unique target distinguished by both low and high levels of representation. The low-level attribute used was curvature and the high-level attribute used was facial expression. We found that visual search operates only on a high-level representation and that low-level representations are no longer accessible to visual search processes when their components become integrated into higher-level representations.

Four visual search tasks were designed using 1) feature vs conjunction targets and 2) the presence/absence of facial organization as the two variables. In Figure 10, each quadrant shows an example of a stimulus array containing one target and five distractors. The target pattern consists of identical elements for all stimulus arrays (one down arc and two up arcs bounded within a circle). The bull's-eye at the center is the fixation point.

In the feature search, the target contained the sole downward arc in the display; in the conjunction search, targets and distractors had both upward and downward arcs and were distinguished only by their spatial arrangement. When there was no facial organization, the arcs were arranged with one on the left and two on the right. When facial organization was imposed, the triplets of arcs were rearranged to suggest two eyes and a mouth. In this case the the target was always smiling and the distractors always frowning.

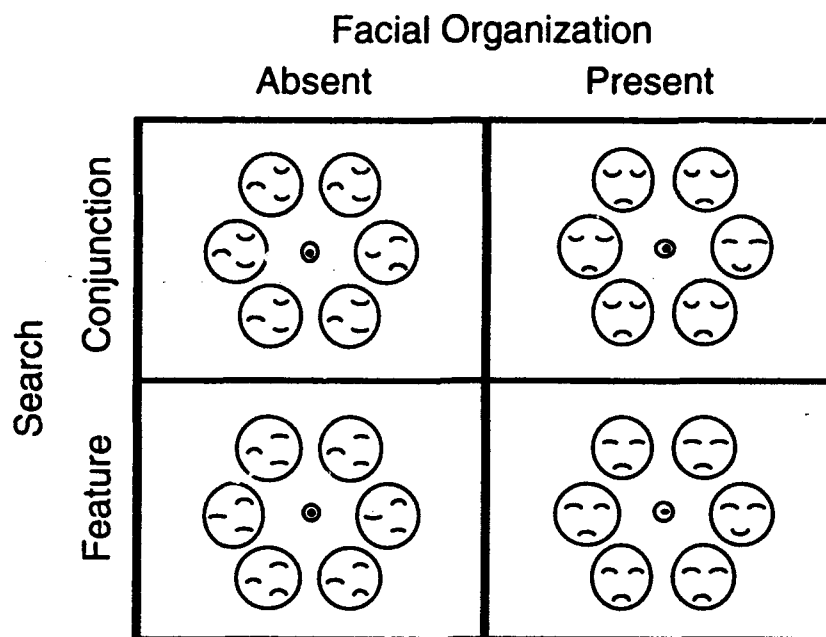


Fig. 10. Search stimuli defined either a feature or conjunction search with or without a facial organization. When the face organization was present, search could be based either on low level curvature features or on high level facial features (expression). The target is always the rightmost element for convenience here. In the actual stimuli, all arcs were identical and differed only in direction of curvature.

The search rate in the conjunction search without facial features was quite slow, consistent with Treisman's conjecture that serial attention is required to conjoin the different features of the target. When these stimuli were arranged in facial expressions, search rates speeded up, suggesting the expected advantage of familiarity. Search rates for the feature condition without facial organization were rapid, again as expected for a feature search. On the other hand, when the facial organization was imposed on these stimuli, search *slowed* down.

The data suggest that facial organization preempts curvature features, making the low-level curvature features "invisible" to the search process when they are parts of a facial organization. This "object inferiority effect" implies that search processes do not have access to all levels of representation but are restricted to a particular high-level representation, high enough for the familiarity of faces to have direct influence on search rates. Moreover, if the stimuli reach the "searchable" level as a complex gestalt such as a face, the search is obliged to operate on those representations even if lower levels of coding, for example, the curves within the face, would offer much faster processing. These results are consistent with those of He and Nakayama (1992) who showed that

when local features are integrated into surface representations, the local features are no longer available to visual search.

6. Visual search: spatial coordinates. Satoru Suzuki and I (Suzuki & Cavanagh, 1993) also examined whether pattern discrimination learning is specific to the location of the target in retinal coordinates or to the location of the target within the array of distractors. The first experiment was a threshold task and the second was a reaction time task. In the training phase of the first experiment, the target, $\equiv$, was placed at location (2,2) in the upper left corner of a 6x6 rectangular array of $\equiv$'s and the array was positioned such that the $\equiv$ fell randomly on one of four training locations (Figure 11a). The task was to decide if the flashed array contained the target. Presentation duration was varied between 50 and 250 msec. Following 20 days of 2400 trials per day, threshold

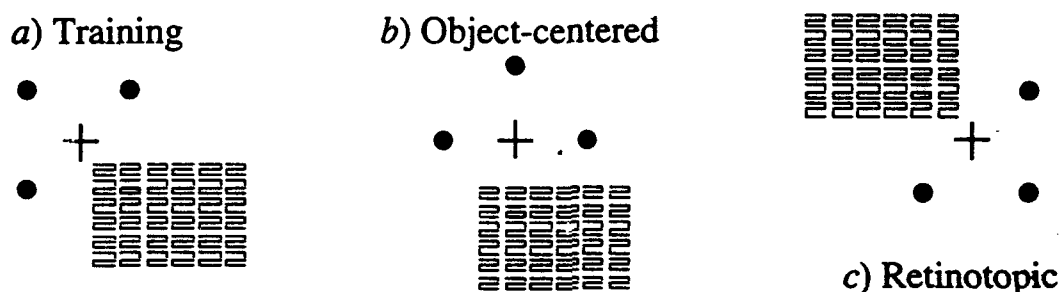


Fig. 11. (a) Observers were trained to detect the sideways 10 which always appeared at the same location within the array of 2's. The four large dots indicate the four training positions for the target (the array moved with the target). To test transfer of training, the target locations were either (b) kept the same within the array but moved to new retinal positions, or (c) kept at the same retinal positions but moved to a new array location.

durations for 75% correct responses dropped from 190 msec to 120 msec. The specificity of this learning was tested by measuring thresholds with modified stimulus arrays and/or locations: retinotopic specificity was tested by rotating the four target locations by 45° (Figure 11b), and object-centered specificity by moving the target item into the lower right corner of the array (Figure 11c) but keeping the retinal locations of the targets the same as during training. The results showed that learning was both retinotopic and object-centered. The learning persisted undiminished over four weeks. In contrast, extended practice on an analogous reaction time task using identical stimuli suggested that learning for this task was object-centered but not retinotopic and also rather short term (reaching plateau/decaying within hours). A manuscript is in preparation.

7. Object features and scene attributes in visual search. Ron Rensink and I (Rensink & Cavanagh, 1993) have shown that shadows are explicitly analyzed at the level of rapid visual search. The search stimuli included objects with typical cast shadows and others with similarly shaped regions which were inappropriate for shadows (Figure 12). We reasoned that shadow regions need to be rapidly identified and suppressed (and perhaps attributed to the background) so that shadow regions may be less available to search processes. The anomalous regions would not be suppressed, however, and should be quite noticeable. This suppression of shadow regions should lead to an interesting asymmetry in visual search rates. Specifically, when the target contains a region interpreted as a shadow and the distractors do not, the target will be defined largely by the absence of a (suppressed) region, and so will be difficult to detect. Switching the items

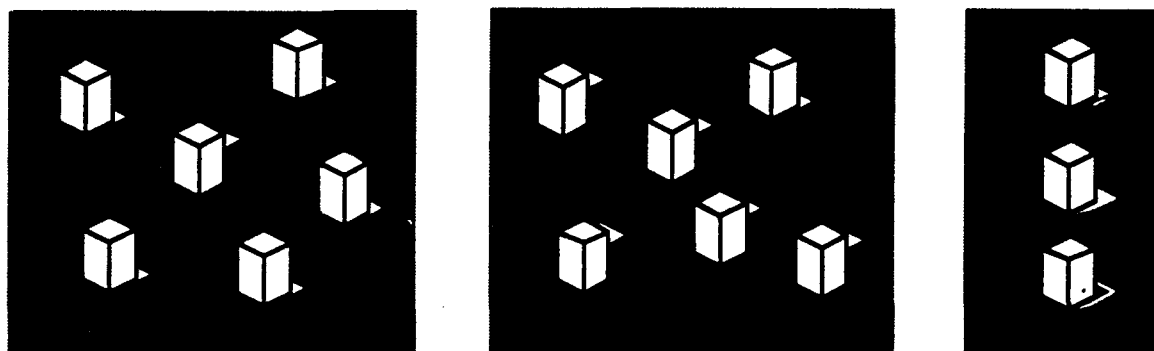


Fig. 12. Shadow search asymmetry. (a) When the target has an anomalous shadow or non-shadow, it stands out, possibly because the normal shadows are suppressed or subsumed into the background surface. (b) When the target has a normal shadow, it is very hard to locate, again because the task requires search for a suppressed feature. (c) Whenever the shadows are manipulated, as in these three examples, to block their interpretation as a shadow, the search asymmetry disappears.

used for target and distractor, however, will lead to fast search, as the target now contains something (i.e., an unsuppressed region) not present in the distractors (Treisman & Gormican, 1988). The results supported this line of reasoning in that search was fast for an object with an anomalous "shadow" among objects with typical shadows (Fig. 12a), but slow for the object with a typical shadow among objects with anomalous shadows (Fig. 12b). Various image manipulations which rendered the shadow areas inappropriate without affecting image geometry (eg, white "shadow" instead of black or outlining the shadow with a thin white contour, Fig. 12c) also eliminated the search asymmetry suggesting that it was specifically the "shadowness" of the attached dark regions which was producing the interesting asymmetry. The general pattern of asymmetries in search speed also differed from that for shaded objects, implying separate handling of shadow-

based and shading-based processes at early levels. As a final point from this research, the asymmetry in search rates disappeared if the displays were presented upside down (Fig. 12 with the page turned upside down), implying that the dark regions were interpreted as shadows only if the light appeared to come from above. In natural scenes, light can come from below and, with unlimited viewing, leads to appropriate identification of shadows. This flexibility for illuminant direction with unlimited viewing appears to be sacrificed in rapid visual search perhaps as one strategy for achieving high processing speeds.

One of the manipulations that eliminated the shadow-based asymmetry in our preliminary studies was to place a short white contour along the cast shadow border (see Figure 12c top). This feature appeared to be a highlight reflection along the edge of the region indicating that it was an actual piece of material with some thickness, strongly ruling out a shadow interpretation for the region.

We believe that our results with shadows are just one example of feature suppression by the visual system. We know that shadows must be rapidly identified and suppressed for object contours to be processed. We predict that other image features like the brightness patterns of highlights and shading may suffer a similar fate. That is, they are identified as features of the scene lighting and become detached from the object and discounted or suppressed. They leave residual effects in the interpretation of the object's surface material but are not easily accessed to determine their actual brightness or shape. This approach will be continued with further studies on rapid analysis of lighting and object features using in particular a new variation of the search task (see Research Methods)

Initial tests of rapid processing of transparency have supported our earlier work (Watanabe & Cavanagh, 1992b) showing that at least some aspects of transparency are available at the level of visual search. Here again we believe that brightness patterns of transparency may be suppressed — specifically in the overlapped region where the brightness is parcelled out to the two separate surfaces and the initial brightness of the region may no longer be accessible.

8. Object recognition: priming. In our model (Cavanagh, 1991), recognition starts with an initial, crude 2-D match that selects a "best" prototype to explain the image data. This is followed by more sophisticated 3-D analyses to complete the recognition process. Our first experiment showed a priming effect of contours in recognition even though many of the contours alone were uninformative for the task. This priming is probing an early (about 100 to 200 msec into processing) 2-D stage of recognition.

This suggests that a contour outline of a shadowed image should be able to initiate the recognition processes that could be appropriately completed if the filled image were then substituted. In our experiment, the prime is the full contour of the image (eg, Fig 13 top left) and is present for a variable duration before the presentation of the filled image (eg, Fig 13 top right). We are interested in how this contour can facilitate the

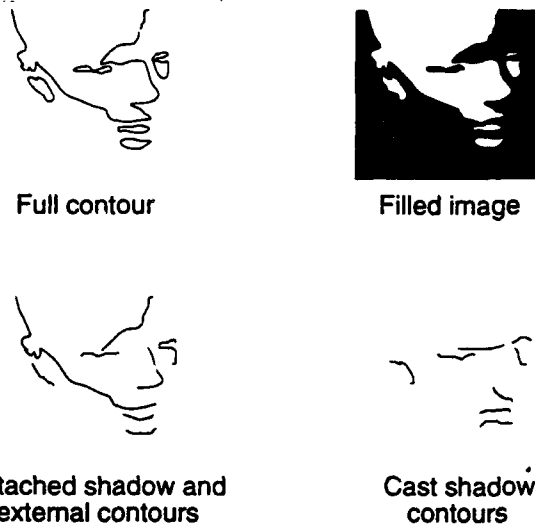


Fig. 13. The contour of a shadowed object may be much more difficult to interpret than the filled, high-contrast image but it contains a highly informative subset of contours which can support a match of the full contour to 2-D prototypes. The cast shadow contours are the reason the full contour is difficult to interpret.

recognition process. Although this contour version may not look like a face at all, its analysis should proceed in a similar manner to that for the filled face up to the point where the image is checked for consistency with the matched prototype (the point at which acceptable interpretations must be found for image contours that did not participate in the match). If this stage begins while the contour representation is still present then the advantages of the prime would be lost — many of the unexplained image contours will be cast shadow borders (Figure 13, bottom right) and the regions within these borders will not be appropriately dark. The face

prototype would be rejected and the potential processing gains all lost. If the filled version is inserted in time, however, the processing gains should be retained.

We did not want to directly ask the observers to recognize the faces, however. Although many of the contour versions of the faces are hard to recognize on their own (as faces), many others clearly look like faces. We therefore devised a new task where the contour itself could give no advance information relevant to the task. In our task, the filled image is presented in either positive or negative contrast and the observer's task is to report which has been presented (Figure 14). When the image is positive, the observer can quickly identify it as a face (all the stimuli were faces) and so knows that it is a positive version. Since we felt that the response is mediated by recognition, we assumed that the priming could play a role in speeding up the recognition. When the image was negative, it was hard to recognize and often seemed a jumble of parts. Subjective reports

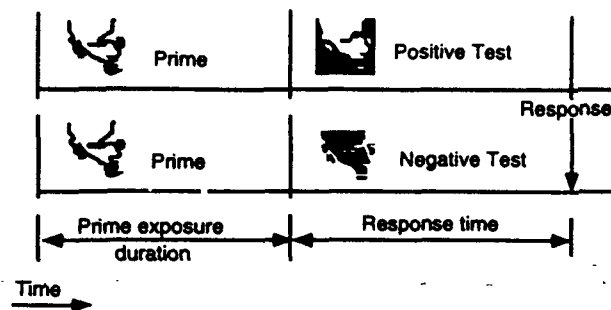


Fig. 14. The prime could be followed by either a positive or negative contrast test and the observer's task was to report rapidly which was presented.

indicated that this lack of a coherent organization mediated the negative responses and since they were not based on recognition, we assumed that priming would not play a role.

The experiment was based on 96 faces seen by 24 subjects. To avoid obvious cues to the contrast, some faces had light surrounds, others dark, some had dark hair, others had light hair (wigs were used), some were

shadowed on the left, others on the right. No subject saw the same face more than once. The contours of the prime and the subsequently presented filled version were physically identical in shape and location in the display. The results (Figure 15) showed a positive versus negative priming effect in reaction time which reached a maximum around 180 msec duration of the prime and decreased afterwards. This result supported the notion of an early 2-D match but still leaves many points to be examined before the theory can be accepted.

In the first control experiment, the unfilled prime and the filled test were from different faces. We found no difference between positive and negative reaction times in this case showing that the effect was not due simply to some alerting signal generated by the contours. We were still concerned about the possible role of conscious processing of the contours, however, some of which could be identified as a face in the contour versions. An additional experiment therefore evaluated the ease of recognition of the contour versions. They were presented either upright or upside-down for 180 msec, followed by a mask.

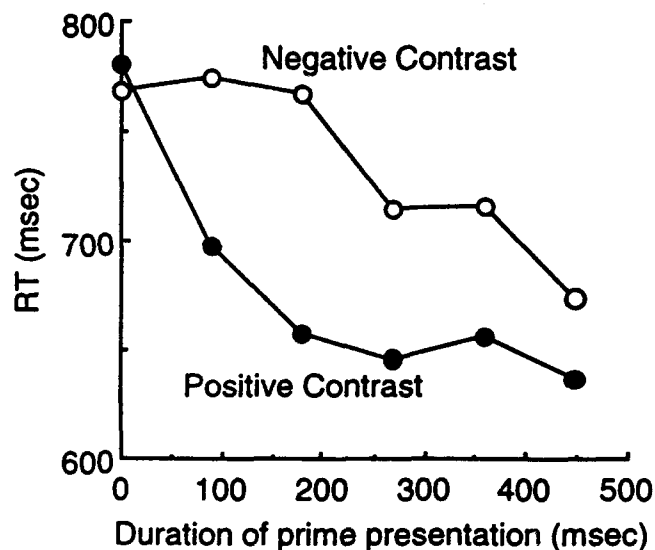


Fig. 15. Response time results for the positive and negative contrast tests as a function of the duration of the prime presentation. The prime facilitates the response to positive contrast tests more than that to negative tests and this difference is at a maximum at 180 msec duration.

The observers had to indicate the orientation of the face. We used these data to rank the contour versions of the faces in terms of difficulty of recognition and then compared the ranking for each face to the priming effect (negative minus positive RTs at 180 msec) found for that face in the first experiment. If consciously recognizable features of the contour versions were producing the priming effect, then the easiest faces to recognize should also show the largest priming. The correlation, however, was negligible (-0.06). We also compiled the reaction times from the original experiment for the most difficult third of the faces. The average error rate in identifying up versus down was 35% for the 32 contour faces with the highest error rates — chance performance was 50%. The average error rate was only 5% for the 64 faces having the fewest errors. Despite these differences in recognition performance, the difficult faces showed a similar pattern and magnitude of priming as the easy-to-recognize faces in the original experiment. Given these results, we are confident that conscious processing of the contours is not mediating the priming effect.

Our final concern was that the contours were simply giving advance information about the location of the contours in the filled image. Our experiment to assess this possibility is described in the Research Methods section. Takeo Watanabe has returned to our lab for the summer where we are collaborating on this extension of the experiments. Specifically, we will use partial contours of the image as primes. In one condition, the contours will be from cast shadow borders and in the other they will be from the most informative external and internal object contours.

Publications during grant period (* indicates support from grant)

- Arguin, M., Cavanagh, P., & Joanette, Y. (in press). Visual feature integration with an attentional deficit. *Brain and Cognition*.
- Arguin, M., Joanette, Y., & Cavanagh, P. (in press). Visual search for feature and conjunction targets with an attention deficit. *Journal of Cognitive Neuroscience*.
- * Cavanagh, P. (1993). The perception of form and motion. *Current Opinion in Neurobiology*, 3, 177-182.
- * Rivest, J., Cavanagh, P., & Lassonde, M. (in press). Interhemispheric depth judgement. *Neuropsychologia*.
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Participating Professionals

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