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Which end is up? Two representations of orientation in visual search

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Abstract

What is the orientation of an object? A simple line has an axis of orientation. That line, turned upside-down, is indistinguishable from the original line. Thus, the possible orientations of a line range from 0 to 180°. Most objects, however, have an axis and a polarity. A polar object, turned upside-down, looks upside-down. Accordingly, the orientations of a polar object range from 0 to 360°. A series of visual search experiments were run to determine if preattentive processes represent orientation in a 180 or a 360° framework. Results suggest that preattentive orientation is represented in 180°. Experiments 1 and 4 show that search for a target rotated 90° from the distractors is more efficient than search for a target rotated 180° from the distractors. Experiments 2, 3, and 5 use a variety of different stimuli to demonstrate that search for targets rotated 180° from distractors is inefficient.

Keywords: Targets; Distractors; Orientation

1. Introduction

Orientation in the frontal plane can be represented in two ways. A simple line is only represented from 0 to 180° since rotations of a line past 180° produce stimuli that are identical to rotations of less than 180°. A vertical line, rotated through 180°, is a vertical line. In contrast, an object can take orientations through 360°. A vertical person, rotated through 180° is still vertical, but upside-down. An upside-down person is recognizably different from an upright person if you are paying attention to that person. Would this 180° difference in orientation attract attention by itself? That is, are 360° of orientation represented by preattentive visual processes or is preattentive processing of orientation limited to 180°?

We have investigated this question in a series of visual search experiments. In a standard visual search task, subjects look for some designated target item among a variable number of distractor items. Reaction time (RT) and accuracy are measured. Assuming that error rates can be held to a relatively low level (e.g. $<$ 10%), the measure of most interest is the change in RT as a function of the number items in the display (set size). When RT $\times$ set size functions have slopes near zero, we have evidence that all items can be processed at once, without capacity limitations. Steeper slopes suggest some capacity limitation. Recent reviews of the search literature can be found in Wolfe (1998a) and Egeth & Yantis (1997). A discussion of the interpretation of search slopes can be found in Wolfe (1998b).

Among the most efficient visual searches are those in which the target is differentiated from the distractors by a single basic feature. Search slopes will be around zero ms/item in searches for a big target among small distractors, red among green, moving among stationary and so forth (Treisman & Gelade, 1980; Treisman & Souther, 1985). Orientation is a clearly established basic feature in this context. For target–distractor differences greater than about 10–15°, a line of orientation X will be efficiently detected among homogeneous distractors of orientation Y (see Fig. 1A and Foster and Ward (1991a,b)). Matters get more complicated when the

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distractors are heterogeneous (Duncan & Humphreys, 1989). For instance, the search for a vertical target will be very efficient if the homogeneous distractors are tilted either 20° to the left or 20° to the right of vertical. However, if the distractors are a mix of 20° left and right, search becomes very inefficient (see Fig. 1B and Wolfe, Friedman-Hill, Stewart and O'Connell (1992a)). Wolfe, Yee and Friedman-Hill (1992b) argued that the preattentive guidance of attention was based on a categorical analysis of orientation. That is, subjects could search efficiently for a target if it was the only steep item in the field, the only shallow item, the only left-tilted item, or the only right-tilted item. Otherwise, search was inefficient, requiring the deployment of attention from line to line at random.

This work and essentially all other systematic work on the preattentive processing of orientation has been done with simple line segments[1]. Taking 0° as vertical

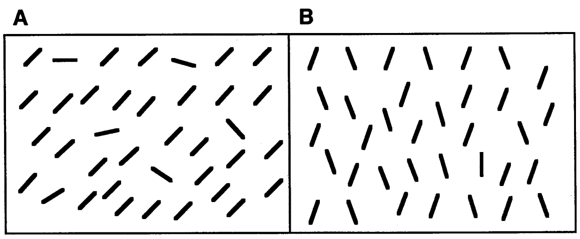

Fig. 1. Basic properties of preattentive orientation processing. (A) Here, there are six targets, ranging in deviation from 15 to 90°. The salience of a target varies with its deviation from homogeneous distractors. (B) When the distractors are heterogeneous, search can be much more difficult as in this search for a vertical item among distractors tilted 20° to the left and right of vertical.

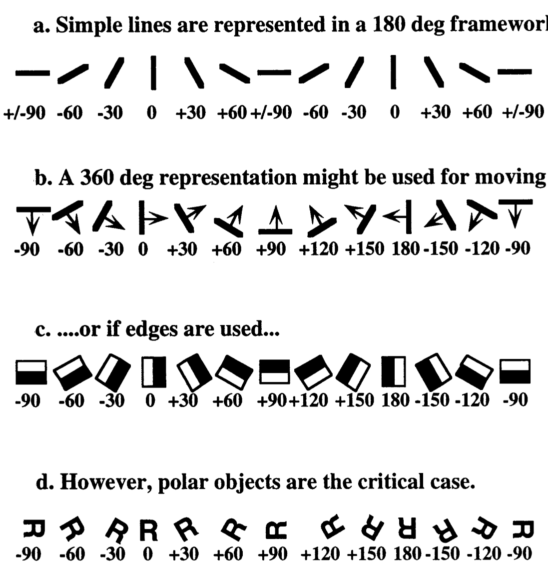

Fig. 2. Reference frames for oriented items.

[1] Many visual search experiments have used stimuli that can be rotated through 360° but these have not been used to probe the nature of preattentive orientation processing.

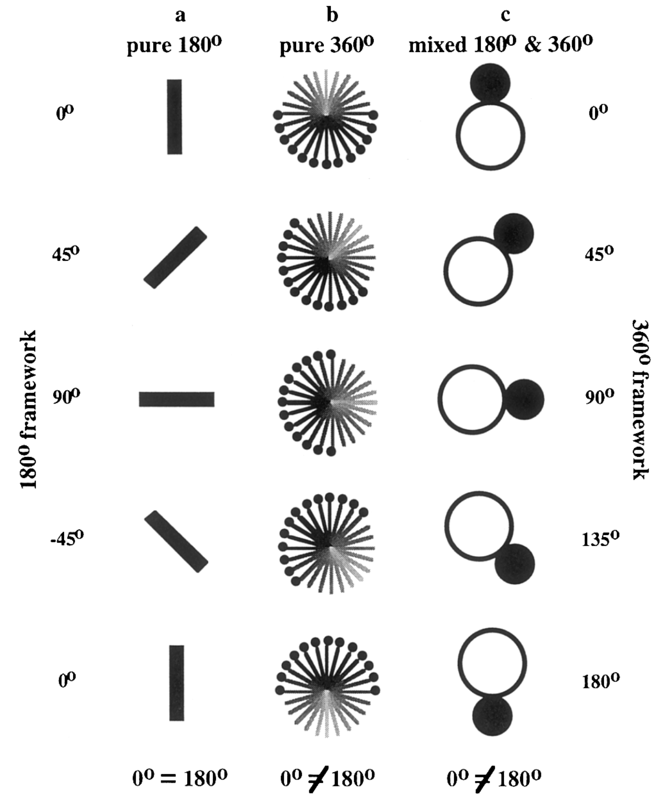

Fig. 3. Three classes of oriented stimuli for visual search experiments. (a) Lines have an axis of orientation. (b). Here the variation in gray level represents a red–green color gradient. These stimuli have minimal or ambiguous axes but have polarity. They differ from their 180° rotations. (c) These *snowmen* have both an axis and polarity.

and using negative values to refer to tilt to the left of vertical, this means that the range of possible orientations is −90 to 90°. Any orientation outside that range is identical to some orientation within that range (Fig. 2a).

There are several situations in which it becomes useful to describe stimuli in a 360° framework. For instance, physiological studies of the orientation tuning of single cells often use moving line segments and then plot the results in a 360° framework in order to differentiate between responses to a vertical stimulus moving left and the same stimulus moving right (Fig. 2b). In this case, the 360° framework actually represents 360° in the direction of motion. Motion is a preattentive feature (Dick, Ullman & Sagi, 1987; McLeod, Driver, Dienes & Crisp, 1991; Nothdurft, 1993a), though parametric study of preattentive sensitivity to motion direction has not been done.

Edges are a class of local features whose orientation needs to be represented through 360° (Fig. 2c). A black–white edge becomes a white–black edge when rotated 180° in the frontal plane. There is some evidence for preattentive sensitivity to edge polarity. This comes in the form of reasonably efficient searches for

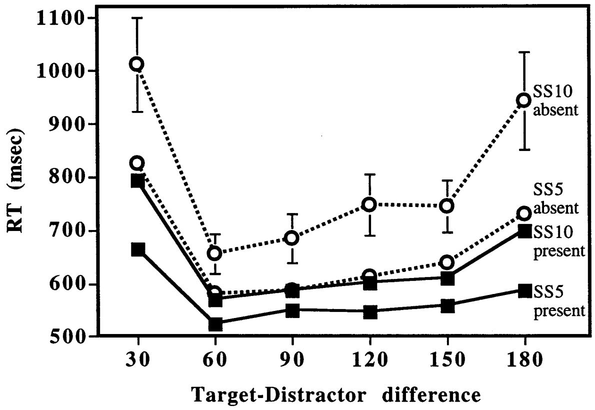

Fig. 4. Mean RTs for Experiment 1. Error bars are ±1 S.E. shown only for set size ten (SS10)-absent trials. Errors for other conditions are smaller.

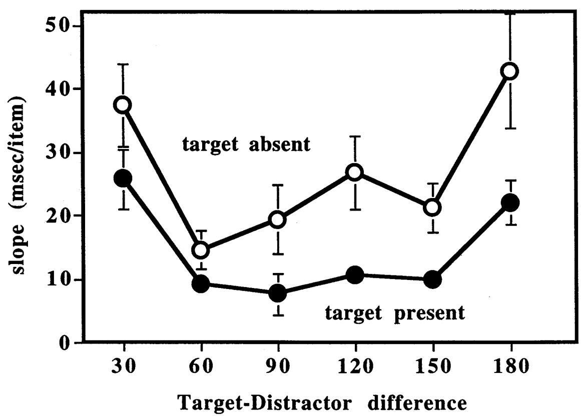

Fig. 5. Slopes for Experiment 1. Error bars are ±1 S.E.

black–white among white–black edges (or equivalent stimuli) (Kleffner & Ramachandran, 1992; Heathcote & Mewhort, 1993; Ponte, Rechea, Sampedro & Carrasco, 1997). Edges are an intermediate case between a line and a typical object. Consider a cube divided vertically into a black, left half and a white, right half. Rotation

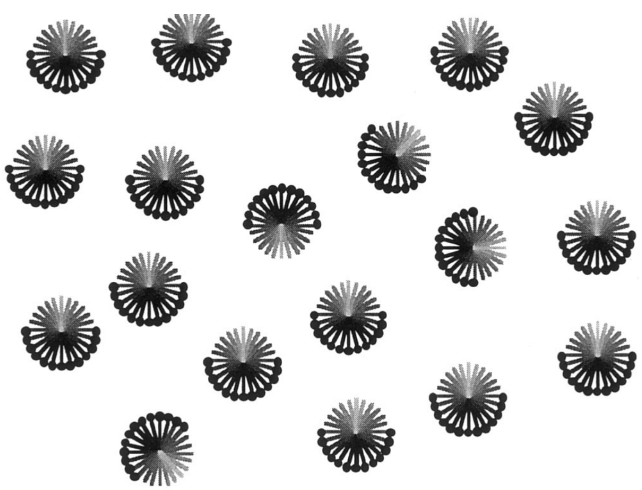

Fig. 6. Stimuli for Experiment 2. Find the four targets that do not have the black row of dots at the bottom.

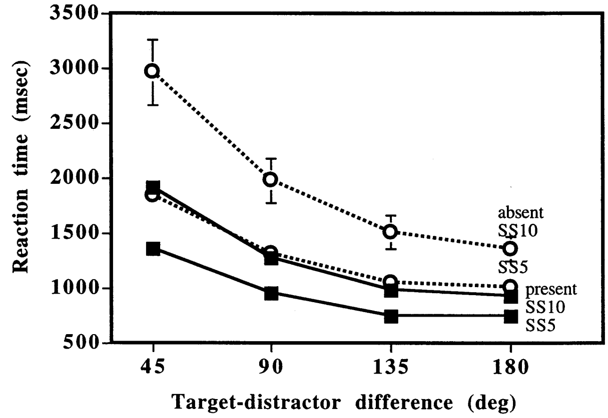

Fig. 7. Mean RTs for Experiment 2. Error bars are ±1 S.E. shown only for the set size ten-absent trials. Errors for other conditions are smaller.

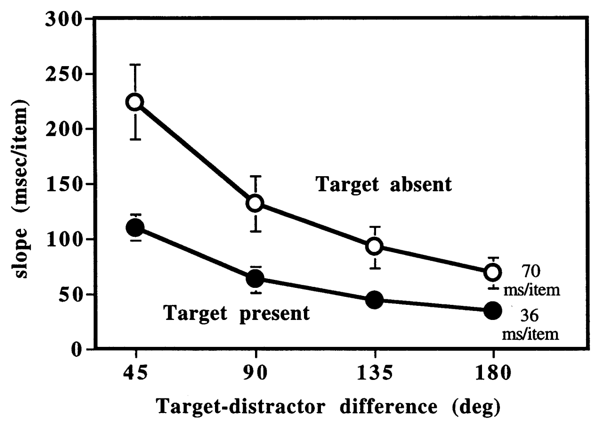

Fig. 8. Slopes for Experiment 2. Error bars are ±1 S.E.

around the line of sight moves black to the right and white to the left. Rotation around either of the other two orthogonal axes leaves the black and white position unchanged. There is some evidence suggesting that preattentive sensitivity to edge polarity may have little to do with the processing of orientation per se and more to do with a sensitivity to lighting direction (Ramachandran, 1988; Enns & Rensink, 1990a; Kleffner & Ramachandran, 1992; Sun & Perona, 1996a).

The critical case for the present discussion is represented in Fig. 2d. While the orientation framework for contours is 180°, most *objects* require an unambiguous 360° for specification of their orientation. When you turn a person upside-down, that person is upside-down, regardless of the axis of rotation. Objects with axes of symmetry are obvious exceptions. Featureless spheres and circles make poor stimuli in the study of orientation. The letter C, rotated 180° around a horizontal axis, is identical to its 0° version. Still, for the bulk of real-world objects, the distinction between 0 and 180° is an important one. Is that distinction represented prior to the point at which attention is directed to an object?

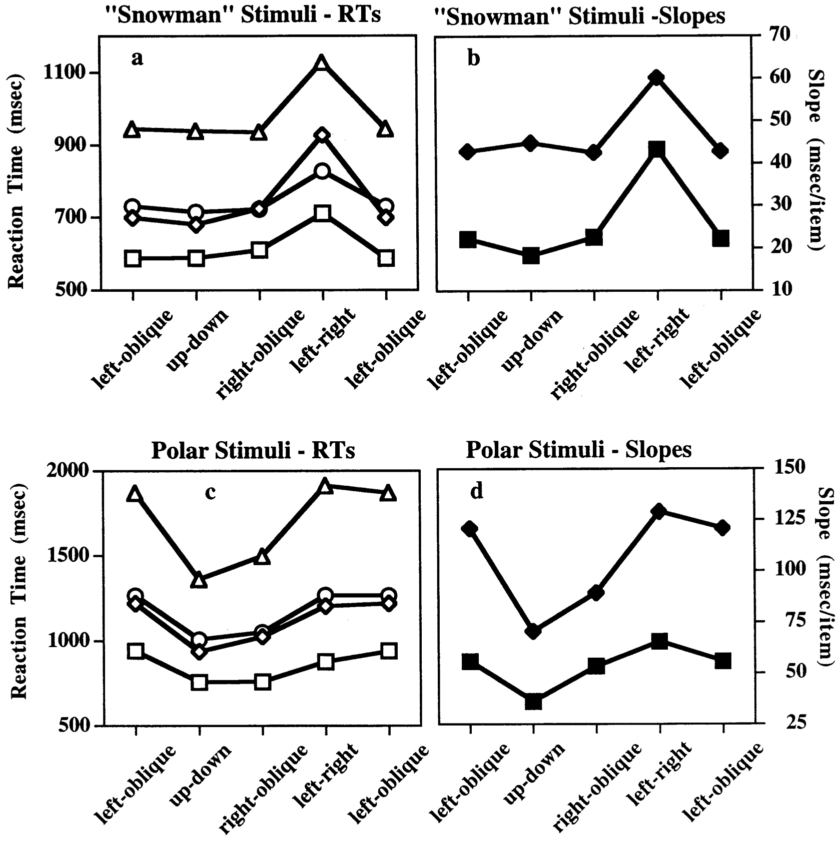

Fig. 9. (a and c) RTs for pairs of targets and distractors separated by 180°: □, set size five, target present; ◇, SS10, present; ○, SS5, absent; △, SS10, absent. (b and d) Slopes of RT × set size functions: ■, target present; ◆, target absent.

The observation that a 360 framework is a property of objects is germane because of the status of objects in preattentive visual processing. There is evidence for preattentive division of the input into some approximation of objects. For instance, attention can be directed to objects (e.g. Tipper, Weaver, Jerreat & Burak, 1994; Vecera & Farah, 1994). If attention is selecting objects, it seems reasonable to assume that there are preattentive objects to select. Preattentive features like color and orientation seem to be only loosely attached to objects (c.f. Treisman & Gelade, 1980). Thus, a cross composed of red vertical and green horizontal elements is preattentively identical to a cross composed of green vertical and red horizontal elements. Preattentively, both crosses are represented as objects with red, green, vertical, and horizontal attributes (Wolfe & Bennett, 1997). The creation of preattentive objects can hide attributes. Thus, if two line segments appear to form a single preattentive object, it is hard to search for a target defined by the properties of either segment in isolation (Rensink & Enns, 1995). As another example, the curve of a line is more easily found if it is not part of schematic face (Suzuki & Cavanagh, 1995).

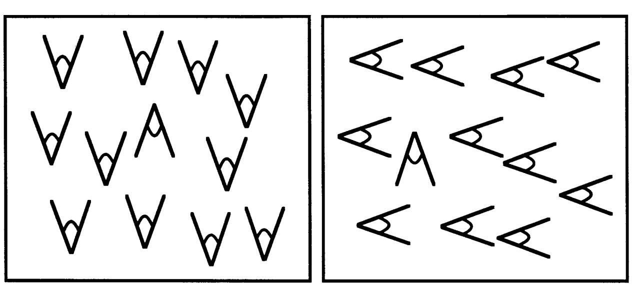

Fig. 10. Stimuli for Experiment 4.

While an object may be represented in the preattentive visual system prior to the arrival of attention, object identification appears to require attention (Wolfe & Bennett, 1997)[2]. Faces, for example, are identified one at a time (Nothdurft, 1993b; Reinitz, Morrissey & Demb, 1994; von Grunau & Anston, 1995; Purcell, Stewart & Skov, 1996). Kahneman and Treisman introduced the idea of an object file that could hold the attributes of a specific object (Kahneman & Treisman, 1984; Kahneman, Treisman & Gibbs, 1992). Wolfe and Bennett (1997) argued that preattentive object files contained a list of the object's basic features and that attention was required to bind those features into a recognizable object.

[2] There has been a recent report of a failure to replicate this finding (Carrasco, Sampedro & Orduna, 1998), however, we have subsequently repeated our experiment using the Carrasco et al. conditions and have successfully obtained our original results.

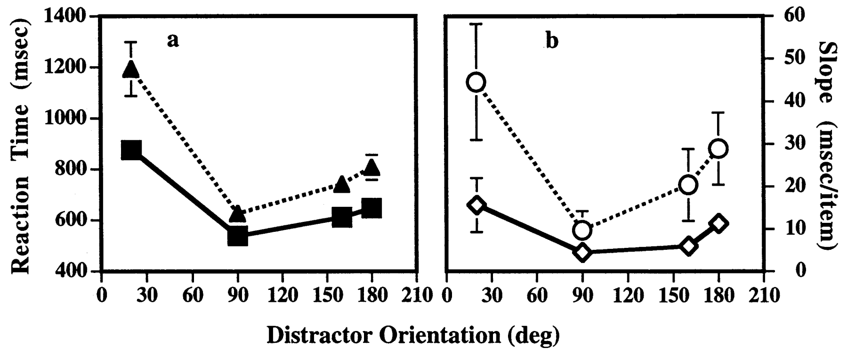

Fig. 11. (a) Mean target-present RTs averaged over all set sizes (■), target-absent RTs averaged over all set sizes (▲). (b) Target-present slopes (◇) and target-absent slopes (○) for Experiment 4. Error bars are 1 S.E. Note that 90° distractors yield more efficient search than 180° while 160° yields more efficient search than 20°.

Returning to orientation, the existing literature does not provide any a priori reason to assume either a 180 or a 360° framework for the processing of orientation in visual search. Prior visual search experiments have been done with stimuli that have only 180° possibilities. The orientational status of the preattentive representation of objects is not known. This paper will present a series of visual search experiments that suggest that orientation is represented in a 180° framework in preattentive vision. The 360° framework has an effect on visual search but probably only as an aspect of attentive processing.

2. Experiment 1: 180 versus 360° representations

We will refer to two aspects of the orientation of an item. An item can have an *axis* of orientation. For our purpose, axis is the sole attribute that defines the orientation of a line. It can vary over 180°. We will say that an item has a *polarity* if that item appears different from a 180° rotation of itself. There are four logical classes of stimuli in this scheme. Items might have polarity and axis, only polarity, only axis, or neither

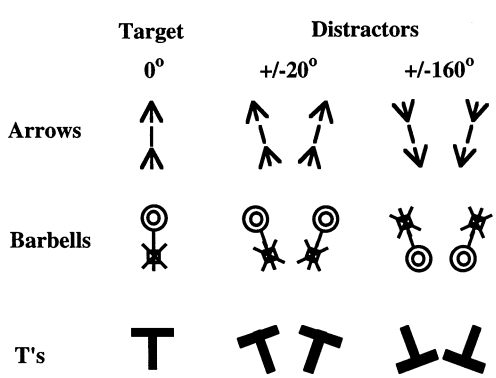

Fig. 12. The three types of stimuli used in Experiment 5.

polarity nor axis. The final class, represented by a circle or a point, is not of interest in a study of orientation since no one will be surprised to discover that it is very hard to find a target circle among distractors rotated by some angle. Our representatives of the three consequential classes are illustrated in Fig. 3.

As noted above, the class of axis without polarity is easily represented by a set of lines (Fig. 3a). The orientations of simple line segments are represented only in a 180° framework. Stimuli from the class of items with polarity but no axis are more difficult to create. Imagine, for instance, a circle with a color gradient, red on top changing smoothly to green on the bottom. This has a polarity. It will also have a weak horizontal axis in the form of a low frequency, color edge. Other polar stimuli have similar problems. Our approach, shown in Fig. 3b, has been to create items with a clear polarity and obscured axis. The gradations of grayscale in the figure stand for the red–green gradient, described above. The lines provide axis information in multiple orientations, obscuring the horizontal color gradient axis and, possibly, a vertical symmetry axis. The row of dots ringing half of the item were gray in the actual stimuli and were intended to enhance the polarity of the items. This is all, admittedly, a bit ad hoc. Nevertheless, as the data for Experiment 2 will show, search for these stimuli seems to proceed on the basis of polarity and not axis.

Items with polarity *and* axis are easy to generate. Our items from this class are shown in Fig. 3c and will be the stimuli for Experiment 1. Each of these 'snowmen' has both an axis, defined by the orientation of its convex hull, and a polarity, defined by the difference in luminance and size between the head and the body. This makes them good stimuli for pitting 180 and 360° frameworks against one another. Circular elements were used for these stimuli so that no local orientation cue could be used to distinguish between rotations of these objects. That is, you could not search for a target by looking for the item with the vertical line segment.

Table 1
Average slopes, confidence intervals, and error rates for Experiment 5

Stimuli	Distractors	Target present slope	±95% C.I	Target absent slope	±95% C.I.	Misses (%)	False alarms (%)
Arrow	Upright ±20	47.5	14.2	99.8	38.7	**23.0**	1.5
	Inverted ±160	17.7	5.7	36.8	9.5	7	0.4
Barbell	Upright ±20	56.1	15.7	91.7	21.9	**22.3**	1.0
	Inverted ±160	38.2	5.1	64.6	8.2	8.3	1.0
T's	Upright ±20	22.6	10.0	62.4	22.4	4.6	1.0
	Inverted ±160	13.6	4.9	32.5	17.7	2.0	0.8

2.1. Methods

In Experiment 1, the target item was always tilted 45° to the left of vertical. A tilted target was used to avoid the possible special status of main axis stimuli (See Section 4 and Section 5). Subjects searched for this target among homogeneous distractors oriented at −15, +15, +45, +75, +105, and +135°. Thus, the angular difference between target and distractors was 30, 60, 90, 120, 150, or 180°. Different angular separations were run in separate blocks of trials. Each block consisted of 200 trials, evenly divided between set sizes of five and ten items and evenly divided between target present and target absent trials.

Stimuli were snowmen, as shown in Fig. 3c. Each subtended 2.2 × 1.4° at the 57.4 cm viewing distance. A 16° square region of a Macintosh computer screen was divided into an invisible 5 × 5 array of cells. Each snowman was placed at a random location within a cell. The search display was visible until the subject made a response. RTs and accuracy were recorded. Accuracy feedback was given after each trial. A total of 30 practice trials were performed by each subject before the experimental trials. Order of blocks was pseudorandom across subjects.

Ten subjects were tested. All gave informed consent and were paid for their time. All had corrected acuity of at least 20/25 and passed the Ishihara color test.

2.2. Results

The distributions of RTs tend to be roughly log normal (positively skewed) making a simple mean a poor measure of central tendency. Accordingly, to decrease the effect of outliers, the mean of log(RT) was calculated for each subject for each set size. These values were then antilogged to produce the estimate of the RT value for that condition for that subject. The averages of these mean RTs for all subjects are shown in Fig. 4 as a function of the angular separation of target and distractors. Fig. 5 shows the slopes of the RT × set size functions for these data.

Errors are scarce (< 4% in any condition) and follow a similar pattern suggesting that change in RT and slope as a function of target–distractor difference is not a speed-accuracy trade-off.

The effect of T–D difference is significant for all functions in Figs. 4 and 5 ($F(5, 9) > 8$, $P < 0.01$, for all cases). It is clear from the figures that performance at 90° is better than performance at 180° for all measures ($F(1, 9) = 6.6$ for set size five, present, $P < 0.05$; $F(1, 9) > 20$ for all others, $P < 0.01$). Linear regressions account for little of the variance in the data (r^2 between 0.00 and 0.02 for all RTs and slopes). Quadratic regressions account for more of the variance (r^2 between 0.15 and 0.34). The minima of these quadratic functions range from 87 to 112. The mean of the minima is 104° with 95% confidence intervals ranging from 95 to 114°. Thus the minima of this function is somewhat greater than 90° but vastly less than 180°.

2.3. Discussion

The stimuli used in Experiment 1 have an axis and a polarity. The efficiency of orientation search using these stimuli seems to be driven primarily by axis orientation in its 180° framework and not by object polarity in its 360° framework. There is a hint of a contribution from object polarity in the asymmetry of the functions relating performance to target–distractor difference. This is to be expected. Even if a 180° representation is driving search performance for these stimuli, search for a polar object among distractors rotated by 180° will still be easier than search for the same target among distractors rotated 0°. The latter search is, of course, impossible while the former is merely hard. Just how much help can be obtained from object polarity is the subject of the subsequent experiments.

These results can be discussed in terms of target–distractor similarity. It is well established that search efficiency increases as the similarity between target and distractors decreases (Duncan & Humphreys, 1989) (for systematic data, see Nagy and Sanchez (1990), Foster and Ward (1991)). These results show that a −45° tilted snowman is more similar in orientation to a 135° tilted snowman than to a 45° tilted snowman. It might be noted that even the most efficient of these searches is not terribly efficient for a simple orientation feature

Table 2
ANOVA results for Experiment 5

Stimuli	Target present/absent	Condition $F(1, 9)$**	Set size $F(1, 9)$**	Slope (conditon X SS) $F(2, 18)$
Arrow	Present	331	99	13.1**
	Absent	22.8	54.2	11.9**
Barbell	Present	20.6	60.0	3.6*
	Absent	37.9	257	16.6**
T's	Present	22.8	41.8	3.1*
	Absent	32.8	31.8	1.3 (n.s.)

* Significance level of at least 0.05.
** Significance level of at least 0.01; n.s., not significant.

search[3]. There are at least two factors that could reduce the efficiency of these searches. First, the snowmen are deliberately weak orientation stimuli. They do not have oriented line segments that can be used to perform the task. The axis must be inferred from the positions of the two component circles. Second, the 90° separation that should yield the most efficient search is handicapped by the mirror symmetry of targets and distractors. Previous work in this laboratory has shown that stimuli symmetrical about a vertical axis are more similar to each other than non-symmetrical stimuli (Wolfe & Friedman-Hill, 1992).

3. Experiment 2: stimuli with polarity but no axis

The efficiency of search in the previous experiment was determined by the orientation of the axis, represented in 180°, and not by the polarity of the object (360°). This suggests that the 180° framework is dominant but it does not offer much insight into the role of the 360° framework. In order to examine the apparently weak effects of object polarity, it is necessary to design stimuli in which an object's polarity is not masked or overwhelmed by the effects of an object's axis. The stimuli shown in Fig. 3b were created with that goal in mind. They have a clear polarity but do not have an unambiguous axis. A starburst was used rather than a simple filled circle because the multiple orientations of the startburst act to obscure any contour created by the gradient.

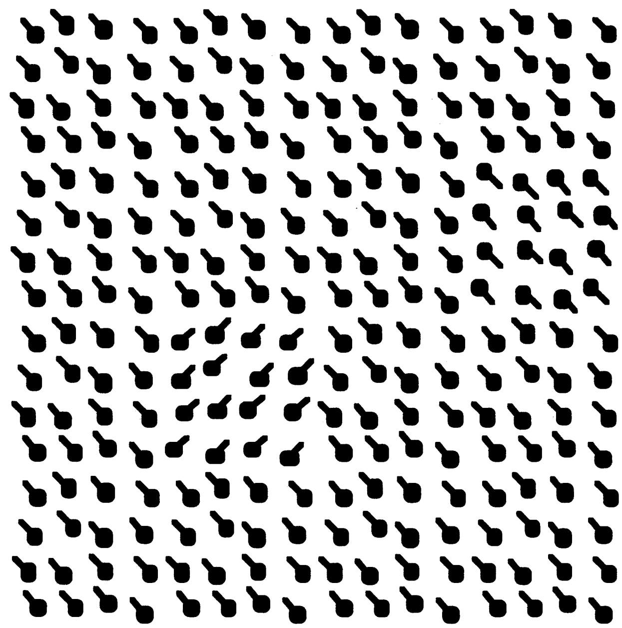

Fig. 13. There are two orientation-defined texture regions that differ from the background. The 90° region is easily found. The 180° region fails to pop-out and probably requires attentional scrutiny.

3.1. Method

In the actual experiments, the gradient ran from red at the top to green at the bottom with gray dots at the end of each line in the lower half of the item. Each item

[3] We describe visual searches in terms of efficiency because it is a theoretically neutral way to discuss the slope of RT × set size functions. It is quite common to describe searches as parallel if they have slopes less than some criterion value like 10 ms/item and to call searches serial if the slope is steeper. Unfortunately, the empirical basis for such a dichotomy is shaky at best (Wolfe, 1998b). This is not the place for an extended theoretical discussion (Wolfe, 1998a). Briefly, then, we hold that the differences in search efficiency arise from differences in the ability of preattentive, parallel processes to guide attention to the target item (Wolfe, 1994). If slopes are near zero ms/item, attention is guided directly to the target. If no guidance is available, search appears to proceed at random through items at a rate of approximately one item every 20–30 ms (Horowitz & Wolfe, 1998). Searches of intermediate efficiency result from imperfect guidance, i.e. attention is biased toward the target but may be deployed to distractor items before finding that target. Thus, in Experiment 1, search slopes should be cut in half if half the items (including the target, when present) were colored red. Attention would be deployed to red items and not to others (Egeth, Virzi & Garbart, 1984). Slopes of greater than 30 ms/item on target present trials suggest that each item is taking a comparatively long time to identify. It is in this context that we would argue that slopes of > 20 ms/item suggest little or no preattentive guidance of attentional deployment.

fit into a $1.8 \times 1.8°$ square. The target was always oriented at 0°-defined by red on top and gray dots on the bottom. Subjects searched for the target among homogeneous distractors rotated clockwise by 45, 90, 135, and 180°. Different target–distractor separations were run in separate blocks of trials. Each block consisted of 200 trials, evenly divided between set sizes of five and ten items and evenly divided between target present and target absent trials. Methods were otherwise identical to those of Experiment 1. Fig. 6 is a demonstration of search through these stimuli. The figure contains four targets, rotated 45, 90, 135 and 180° from the distractor orientation.

3.2. Results and discussion

RTs were calculated as the antilog of the mean of log RT for correct responses for each subject. The averages of these mean RTs for all subjects are shown in Fig. 7 while Fig. 8 shows the slopes of the resulting RT × set size functions.

Errors are quite low ($< 7\%$ in any condition) and follow a similar pattern to the RTs and slopes. Harder conditions produce slower RTs, higher slopes, and more errors.

The effect of T–D difference is significant for all functions in Figs. 4 and 5 ($F(3, 9) > 20$, $P < 0.01$, for all cases). In a reversal of the previous experiment, performance at 180° is better than performance at 90° for all measures ($F(1, 9) > 17$, for all four RT measures, $F(1, 9) = 11.6$, $P < 0.01$ for target absent slopes; but $F(1, 9) = 4.9$, $P > 0.05$ for target present slopes). Linear regressions explain a significant portion of the variance (r^2 range from 0.36 to 0.56). Adding a quadratic term contributes little ($r^2 = 0.39–0.64$).

Note that, while the minimum is at 180° and not at 90°, that minimum is not very minimal. As shown in Fig. 8, the mean slopes for target present and target absent drop only to 36 and 70 ms/item, respectively. This is comparable to classic 'serial searches' like the search for a rotated T among rotated Ls (Kwak, Dagenbach & Egeth, 1991; Horowitz & Wolfe, 1998). For comparison, the slopes for the snowman stimuli of Experiment 1 are 18 and 44 ms/item for the same orientations. Thus, with a 180° target–distractor difference, search is inefficient with either set of stimuli. The greater inefficiency of the stimuli of Experiment 2 may reflect the stronger polarity of the black and white snowman stimuli.

In the absence of axial information, orientation search becomes inefficient. It is modulated by object polarity in a 360° framework but that modulation is a modulation between inefficient and extremely inefficient search[3]. The failure to find efficient search based on object polarity is a negative finding and, consequently, must be approached with caution. Perhaps we chose poor stimuli. Experiments 4 and 5 examine some other possibilities. Alternatively, we might have chosen the wrong axis. With the stimuli in Experiment 2, we placed the red lines on the top and the green lines and gray dots on the bottom of the target. Perhaps polarity-based search would improve if the stimuli were rotated to some other axis while maintaining the 180° separation between targets and distractors. This was tried in Experiment 3.

4. Experiment 3: axis manipulations

In each block of this experiment, the target was of one orientation and the distractors were all oriented 180° away from that orientation. Thus, if the target was the upright, 0° snowman in Fig. 3c, the distractor would be the upside-down, 180° snowman. Since 180° is the maximum separation between target and distractors in a 360° framework, these conditions were designed to give object polarity information its best chance to guide attention.

4.1. Methods

This experiment used the stimuli and methods of Experiments 1 and 2. Indeed the eight blocks of trials that constitute Experiment 3 were run intermixed with either Experiment 1 or 2, depending on which stimuli were being used. In all conditions, the relative separation between target and distractor orientations was 180°. What changed between conditions was the absolute orientation of the items. A *left-oblique* condition had a target of −45° and homogeneous distractors of 135°. The *up-down* condition used 0 and 180°, *right-oblique* −45 and 225°, and *left-right* −90 and 270°. Data from the snowman *left-oblique* condition and the polar object *up-down* condition were previously reported as parts of Experiments 1 and 2, respectively, and are replotted. Methods were identical to those in Experiments 1 and 2.

4.2. Results

Fig. 9 shows the RTs and slopes for snowman and polar object data. *Left-oblique* data are plotted redundantly on the left and right of each panel to produce a continuous picture of the effect of change in axis.

There is a significant effect of condition for both types of stimuli for RTs and for slopes (All $F(3, 27) > 5.6$, $P < 0.01$, except for the snowman, target present slopes, $F(3, 27) = 2.7$, $P > 0.05$). The two sets of stimuli agree in finding that up-down is more efficient than left-right (All $F(1, 9) > 6.2$, $P < 0.02$). Using the snowman stimuli, the oblique conditions are comparable to the best, up-down condition. Using the polar object stimuli, the oblique conditions are intermediate. Note that none of these searches are particularly efficient. The most efficient yields slopes of about 15 ms/item for target present and 45 ms/item for target absent. If there were any preattentive representation of 360° of orientation, we would expect to find efficient search targets and distractors separated by 180° in, at least, some condition. No such evidence appears from Experiment 3. Rather, the data support the hypothesisn that object polarity information is available only when attention is directed to the object. The axis of object polarity does have an effect on search but that effect appears to be a modulation of inefficient search. Once attention is directed to an object, it appears to be easier to differentiate top and bottom than left and right—an observation that will come as no surprise to anyone who has ever tried to teach a child to discriminate the left hand from the right.

5. Experiment 4: pencil point stimuli

The experiments thus far argue for the position that 180° information is available for the preattentive guidance of attention while 360° information is not. As noted above, one might object that these conclusions are based on only two types of stimuli. Accordingly, we have examined search for a variety of other stimuli having an axis in the 180° framework and a polarity in the 360° framework.

5.1. Methods

Examples of the stimuli for Experiment 4 are shown in Fig. 10. These are built on the letter V. However, as with the previous stimuli, some care must be taken to avoid introducing cues other than orientation into the task. In this case, direction of curvature (e.g. smile vs. frown) might be represented preattentively (Simmons & Foster, 1992; Wolfe et al., 1992b; Nothdurft, 1993b). To weaken that cue in this case, we place an interior arc with the opposite sign of curvature in each of the elements. In each element, the angle formed by the two lines is 40°. The orientation of the whole item can be defined by the orientation of the axis of symmetry. Thus, in Fig. 10, the targets are oriented at 0°. The distractors are oriented at 180° in Fig. 10a and −90° in Fig. 10b. Stimuli subtended $1.7 \times 1.8°$ at the 57.4 cm viewing distance.

There were four conditions in Experiment 4. All had the same, 0° target. The four conditions differed only in the orientation of the homogeneous distractors. These could be rotated 20, 90, 160, and 180° from the vertical target orientation. Ten subjects were tested. Each subject was tested for 300 trials each in each of the four conditions of the experiment. Before running each condition, the subjects completed a practice block of 30 trials. Three set sizes were used: six, ten, and 14 items. All other methods were comparable to those in the previous experiments.

5.2. Results

The slopes and mean RTs for this experiment are plotted in Fig. 11.

There are two comparisons that are of particular interest: 90 versus 180° and 20 versus 160°. Is the search more efficient with the 90 or the 180° distractor? ANOVAs comparing the 90 and 180° RTs were performed with distractor orientation and set size as factors and subjects as the error term. For target present trials, the main effects of RT and set size were significant ($F(1, 8) = 23.3$, $P < 0.01$; $F(2, 16) = 24.6$, $P < 0.01$). The slope difference, as assessed by the interaction of RT and set size is also significant, ($F(2, 16) = 12.9$, $P < 0.01$). This is supported by a paired t-test on the slopes, ($t(8) = 2.8$, $P < 0.025$). The picture was similar for the target absent trials. Main effects of RT and set size were significant ($F(1, 8) = 18.9$, $P < 0.01$; $F(2, 16) = 10.9$, $P < 0.01$) as was the interaction of RT and set size ($F(2, 16) = 6.7$, $P < 0.01$) and a paired t-test on the slopes, ($t(8) = 2.8$, $P < 0.025$). All of these results support the hypothesis that search among 90° distractors is significantly more efficient than search among 180° distractors.

The 160° distractors are the 20° distractors turned upside-down and reflected around a vertical axis. More efficient 160° search would be evidence in support of a role for object polarity. In this case we find evidence that the 160° search is faster (RTs) but only weak evidence that the 160° search is more efficient (slopes). For target-present trials, the main effects of RT and set size were significant ($F(1, 8) = 16.5$, $P < 0.01$; $F(2, 16) = 7.9$, $P < 0.01$). The interaction, measuring the slope difference, just reaches statistical significance ($F(2, 16) = 3.4$, $P < 0.05$, while a paired t-test on the slopes themselves does not ($t(8) = 1.8$, $P > 0.1$). The story is similar for target absent trials. Main effects of RT and set size were significant ($F(1, 8) = 9.6$, $P < 0.05$; $F(2, 16) = 14.7$, $P < 0.01$). The interaction, measuring the slope difference, failed to reach statistical significance ($F(2, 16) = 3.0$, $P > 0.05$ as did the paired t-test on the slopes $t(8) = 1.6$, $P > 0.1$). The difference between 20 and 160° that can be seen in Fig. 11b may be real but the data are too variable to be persuasive.

Error rates were low (< 3%) for all conditions except for the 20° condition which produced a 6% miss rate.

5.3. Discussion

These data are consistent with the pattern of results from the previous experiments. The best performance occurs when targets and distractors differ by 90°. There is some evidence that search among 160° distractors is easier than the search among 20° distractors but the evidence is only convincing for RT and not for slope. The greater errors in the 20° condition suggests that slope may have been underestimated in that condition (a speed-accuracy tradeoff) but the error rate is not large and so the trade-off is not likely to be great. Overall, the experiment produces more evidence for a 180° framework for preattentive orientation processing.

6. Experiment 5: other stimuli

The failure to find clear evidence in favor of preattentive processing of object polarity suffers from the usual problem with negative findings. It is always possible that we simply used the wrong stimuli. Accordingly, we present results obtained with a variety of other stimuli.

6.1. Methods

Experiment 5 used a slightly different search task. Wolfe et al. (1992a, 1992b) demonstrated that search was very inefficient when the target was vertical while the distractors were tilted to the left and right of vertical (see Fig. 1B). In Experiment 5, we tested the hypothesis that such inefficient searches would become efficient if the target was upright and vertical while distractors were upside-down and tilted to the left and right. That is, we tested the hypothesis that the addition of object polarity information could be used to support efficient visual search.

Three types of stimuli were used as shown in Fig. 12. The target was always the vertical item. Two conditions were tested with each type of item. In the upright condition, distractors were tilted 20° to the left and right of vertical. In the inverted condition, distractors were rotated 160° to the left and right of vertical. The 160° distractors are 180° rotations of the 20° distractors so distractors in the two conditions had the same axes of orientation but different object polarity.

Arrow stimuli fit inside a virtual rectangle of $2.5 \times 1.0°$g at the 57.4 cm viewing distance. Barbell stimuli fit into a rectangle of $1.9 \times 3.0°$ and the Ts fit into a rectangle of $1.6 \times 1.6°$.

Ten subjects were run with each set of stimuli. Some subjects were tested with more than one set of stimuli. All subjects could pass the Ishihara Test for Colorblindness and had corrected acuity of at least 20/25. Each subject performed ten blocks of 30 trials each for upright and inverted conditions. Before running on each condition, the subjects completed a practice block of 30 trials. Three set sizes were used: six, ten, and 14. Accuracy rates and reaction times were measured. Vsearch software was used to present stimuli on Macintosh computers (Enns, Ochs & Rensink, 1990). Targets were present on 50% of the trials. The order in which conditions were presented was pseudorandom across subjects.

6.2. Results and discussion

Table 1 gives average slopes of the RT × set size functions for all three stimulus types. Also in Table 1 are the 95% confidence intervals for those slopes and the miss and false alarm error rates. Error data are tabulated here because, unlike Experiments 1–4, Experiment 5 generated some very high error rates (noted in boldface).

The first broad point to be drawn from these results is that the inverted conditions are consistently faster and more efficient than the upright conditions. This is borne out in the ANOVA results shown in Table 2. For each type of stimuli, separate ANOVAs were computed for target-present and target-absent trials using condition (upright vs. inverted) and set size as factors and using subjects as the noise term. The significant effects of condition show that upright was slower than inverted in all cases. The set size main effects merely confirm a slope greater than zero ms/item. The interaction of condition and set size measures the difference in slopes between the upright and inverted conditions. Upright is significantly steeper for arrows and barbells but, at best, marginally so for the Ts. Note also that the error rates for the Upright conditions are markedly higher than the inverted rates, accentuating the difference between the conditions.

The second broad point to be drawn from these data is that, while inverting the distractors makes the tasks more efficient, it does not make them particularly efficient in absolute terms. Target present slopes are always markedly greater than zero. Target absent slopes are steeper still. Turning the distractors upside-down converts the search for a vertical target from catastrophically inefficient to merely inefficient[3].

Consistent with the previous results, there is no strong evidence in these data for preattentive processing of object polarity. Rather, these data are consistent with the notion that inverting one of these distractors makes it easier to categorize it as a distractor once attention has been directed to it. That is, a 20° distractor may take longer to reject than a 160° distractor.

7. General discussion

The experiments presented here indicate that preattentive orientation information is represented in a 180° framework and not in a 360° framework. The most efficient searches for an oriented target among homogeneous distractors are obtained with a target–distractor difference of 90° (Sections 2 and 5). When the sole source of orientation information is object polarity, searches are inefficient (Sections 3, 4 and 6). The nature of polarity information does modulate search efficiency. For instance, it is easier to find a 0° (vertical) target among 180° (vertical) distractors than it is to find −90° (horizontal) among 90° (horizontal) (Section 4). However, these modulations all appear to be modulations of inefficient searches. In no case did the addition of polarity information make an inefficient search into an efficient search.

As noted before the conclusion that object polarity does not support efficient search is a negative finding. It is always possible that we simply used the wrong stimuli. We were constrained in the design of stimuli because we needed to avoid introducing irrelevant features that might masquerade as preattentive processing of object polarity. For instance, a simple curve, "can be found efficiently among curves rotated through 180°" (Wolfe et al., 1992b), but that would seem to be a special case of curvature processing, not a general demonstration of object polarity processing. Similarly, there is evidence for preattentive processing of lighting direction and orientation in 3 D space (Enns & Rensink, 1990a,b; Kleffner & Ramachandran, 1992; Sun & Perona, 1996a,b). Thus, one can search efficiently for rendered cubes, spheres, etc. among 180° rotated cubes, spheres, etc. As with curvature, these results would not be evidence for processing of object polarity, as such. Natural objects might be a promising place to look for evidence of preattentive polarity processing, though the stimulus control problems are quite daunting.

It is important not to overgeneralize negative findings about preattentive processing. If a feature supports efficient search, then it is reasonable to conclude that this feature is represented preattentively. However, if a feature does *not* support efficient search, it is *not* safe to conclude that this feature is *not* represented preattentively. There are, at least, two reasons why a feature might not support efficient search: (1) the feature might not be computed preattentively; or (2) the feature might be represented preattentively but be unavailable to guide attention (Wolfe & Horowitz, 1998). That is, it is possible that attention is guided by only a subset of the information available in the preattentive stages of visual processing. Here, as elsewhere, it is helpful to have converging operations to support hypotheses. In the case of preattentive vision, the case is stronger if texture and visual search data agree (Treisman, 1986; Wolfe, 1992).

We have not performed formal texture segmentation experiments on sensitivity to object polarity. However, demonstrations like that shown in Fig. 13 strongly suggest that object polarity will not support texture segmentation any more than it will support efficient visual search. In the figure, a 90° rotation of a set of the texture elements produces clear texture segmentation. A 180° rotation does not.

To reiterate a point from Section 1, our failure to find evidence for preattentive processing of object polarity is interesting given the ever-increasing evidence for the preattentive processing of objects (e.g. Hillstrom & Yantis, 1994; Vecera & Farah, 1994; Yantis & Gibson, 1994; Wolfe, 1996; Tipper & Weaver, 1998). Attentional selection seems to operate on a representation of the visual world that has been divided into a set of objects of some sort. Those preattentive objects may lack many of the attributes of full-fledged perceptual objects. For instance, it does not appear to be possible to direct attention on the basis of the overall shape of an object in the absence of other feature cues (Wolfe & Bennett, 1997)[2]. The results of the present experiments suggest that preattentive objects do not represent polarity information in a way that can be used to support efficient visual search.

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