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Vision Research 46 (2006) 4258–4269
Vision Research
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Eye dominance effects in feature search

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Received 10 April 2006; received in revised form 24 July 2006

Abstract

We studied the role of eye dominance in non-rivalry conditions, testing dichoptic visual search and comparing performance with target presented to the dominant or non-dominant eye. Using red–green glasses, subjects viewed an array of green and red lines of uniform orientation, with a differently oriented target line present on half the trials. Performance was significantly better when the dominant eye saw the target, especially when the opposite eye saw the distractors. This effect was reduced when only nearest-neighbor surrounding distractors were homogeneous. We conclude that the dominant eye has priority in visual processing, perhaps including inhibition of non-dominant eye representations.

Keywords: Eye dominance; Visual search; Binocular vision; Surround effects

1. Introduction

1.1. Eye dominance

Eye dominance is the tendency to prefer visual input from one eye to input from the other (e.g. Porac & Coren, 1976). Dominance may be determined genetically (Brackenridge, 1982; Merrell, 1957; Zoccolotti, 1978; but see Porac & Coren, 1979). This preference leads to numerous perceptual effects: Subjects are more accurate using their dominant eye (Coren, 1999; Freeman & Chapman, 1935; Lund, 1932); images appear clearer (Porac & Coren, 1984) and larger (Porac & Coren, 1976; but see McManus & Tomlinson, 2004) when viewed by the dominant eye; and stabilized retinal images fade slower when viewed by the dominant eye (Porac & Coren, 1982). Schoen and Scofield (1935) found that diplopia threshold (i.e. the extent to which the eye overcomes prismatic stress before binocular single vision is disrupted) is greater for the dominant eye. Imaging studies with monocular stimulation found more, i.e. larger area, bilateral activation when the dominant eye was stimulated (Menon, Ogawa, Strupp, & Ugurbil, 1997; Rombouts, Barkhof, Sprenger, Valk, & Scheltens, 1996). Recently, Oishi, Tobimatsu, Arakawa, Taniwaki, and Kira (2005) found that the dominant eye is functionally activated prior to the non-dominant eye following a horizontal saccade during reading. Taken together, these phenomena suggest that inputs from the dominant eye may be more sensitive, responsive or numerous, and/or may capture attention more readily, leading to a more salient percept.

While some early studies reported a connection between eye and hand dominance (Crovitz & Zener, 1962; Sampson & Spong, 1962), others found no relation between them (Annett, 1999; Coren & Kaplan, 1973; Gronwall & Sampson, 1971; Papousek & Schulter, 1999; Pointer, 2001 Porac & Coren, 1975, 1976; Snyder & Snyder, 1928). Note that hemisphere dominance can underlie hand dominance, but not eye dominance, since each eye projects to both hemispheres.

It has been argued that eye dominance is a relatively fixed phenomenon, because most adults show a consistent preference for the left or the right eye (Porac & Coren, 1976). On the other hand, eye dominance may switch from one eye to the other with changes in horizontal eye position (Carey, 2001; Khan & Crawford, 2001, 2003) and with

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0042-6989/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.visres.2006.08.006

modulation of the hand being used, perhaps because eye-hand coordination uses the eye with the best overall field of view (Khan & Crawford, 2001, 2003). Banks, Ghose, and Hillis (2004) claimed that eye dominance may switch from eye to eye with changes of relative image size.

There are three common criteria for determining eye dominance (Coren & Kaplan, 1973): (1) The eye with better visual acuity (VA), contrast sensitivity, or other measure of visual function. (2) The eye in which a rivaling stimulus is most often perceived. And, (3) the eye used for sighting (e.g. when one looks at a distant object through a ring held in both hands, with both eyes open). Despite a remarkable number of early studies that found discrepancies between different eye dominance tests (Coren & Kaplan, 1973; Gronwall & Sampson, 1971; Hebben, Benjamins, & Milberg, 1981; Mills, 1925; Osburn & Klingsporn, 1998; Porac & Coren, 1976; Schoen & Scofield, 1935; Walls, 1951), recent evidence suggests a positive correlation between these three criteria: The sighting test correlates with the binocular rivalry test (Handa et al., 2004) and with near-point monocular acuity (Porac, Whitford, & Coren, 1976), perhaps related to the fact that at the near point, where vision becomes diplopic, dominance determines which image is perceived. In addition, the eye with better VA tends to be the one chosen for sighting (Porac & Coren, 1976), though, once established, dominance resists optical degrading (Coren & Porac, 1977).

There are many versions of the sighting test, including the Porta (1953) Test (observers position a near stimulus—a pencil or finger—so that it appears collinear with a distant stimulus; the Hole in the Card Test (Durand & Gould, 1910; subjects sight a target through a hole in the middle of a card); and the Miles (1929) Test (subjects peer through a hole in the narrow far end of a cone at a distant target). Test–retest reliability is high (Miles, 1928, 1929; Porac & Coren, 1976) and different sighting tests demonstrate consistent preferences (Coren & Kaplan, 1973; Crider, 1944; Gronwall & Sampson, 1971; Miles, 1930; Porac & Coren, 1976; Walls, 1951), suggesting that there is a single sighting-dominant eye for each person (Mapp, Ono, & Barbeito, 2003). Thus, sighting—e.g. the Hole in the Card Test—may be the most behaviorally significant way to test dominance (Porac & Coren, 1976). However, there is evidence that sighting dominance may depend on the observer's knowledge about the task (Miles, 1929), on the direction that the card is moved in the Card Test (Ono & Barbeito, 1982), on the gaze angle (Khan & Crawford, 2001), and on which hand the subject uses for the test (Carey, 2001).

The function of eye dominance is not fully understood. In their recent review, Mapp et al. (2003) suggested that the sighting dominant eye is the eye which is used for monocular tasks and has no unique functional role in normal binocular vision. For example, Gates & Bond (1936) found no consistent effects of eye-dominance or single eye superiority in acuity, related to achievement in reading, word pronunciation, reversal errors, or visual perception of various items. On the other hand, a recent study by Roth, Lora, & Heilman (2002) showed that attentional systems may be activated differently by the two eyes. They used a line-bisection-in-depth task and found that eye dominance predicted whether subjects would have a reduced far bias for monocular stimuli in central space. Walls (1951) argued that sighting dominance may be related to eye-movements with the dominant eye initiating muscular adjustments involved in fixation, and the non-dominant eye making corresponding reflexive motions to maintain binocular fusion. According to this view, the major perceptual difference between the eyes should be found when perception involves motor function. Indeed, Money (1972) found that perceptual accuracy was significantly higher when viewing with the dominant eye, but only when digit recognition or spatial localization involved scanning (i.e. motor function).

There is evidence also for general superiority of the dominant sighting eye: Information from this eye may be processed more rapidly, as seen in reaction time (Minucci & Conners, 1964) and search and recognition studies (Money, 1972; Porac & Coren, 1979; Sampson & Spong, 1962). Furthermore, dominant eye monocular afterimages of a vertical line remain visible longer (Wade, 1975), perhaps because there is less inhibition from the non-dominant eye. Similarly, when subjects view checkerboard stimuli dichoptically, there is different striate activation when the stimuli are presented to both eyes, each eye, or in an alternating condition (Büchert et al., 2002), again perhaps due to inhibitory interactions across ocular dominance columns. In certain circumstances, such differences allow subjects to know from which eye a stimulus initiates (Blake & Cormack, 1979), but generally ocular dominance may be insufficient for such utrocular discrimination (Porac & Coren, 1986).

The goal of the present study was to find if there is a behavioral effect of performing a perceptual task with the dominant vs. the non-dominant eye. We chose for our testing paradigm the rapid feature search task, also referred to as "pop-out" search.

1.2. Feature search

Detection of an element that differs significantly from surrounding elements, even in a single dimension such as orientation, is an easy task (Treisman, 1988; Treisman & Gelade, 1980). The odd element is said to "pop-out" and its detection is rapid and parallel, i.e., independent of the number of distractors, (Treisman & Gelade, 1980; Treisman & Souther, 1985). This type of perceptual task is called Feature Search and is distinguished from slower searches such as Conjunction Search, which require use of focused attention and result in a linear increase in search time with the number of items in the display (Treisman, 1982, 1988; Treisman & Gelade, 1980).

We evaluated the relationship between eye dominance and performance on a visual search task. We particularly wanted to test if the dominant eye has priority in visual perception, and if it performs visual tasks better than the non-dominant eye.

1.3. Arrangement of distractor elements

For feature search, it is expected that performance will depend on the target-distractor difference, i.e. performance will improve with larger categorical differences. To test the effect of eye-dominance, we controlled the eye through which subjects viewed both the target and the surrounding distractor elements. The three cases that we compared are: *Same*: distractor elements were presented to the same eye as the target itself (whether dominant or non-dominant); *Opposite*: distractors elements were presented to the opposite eye; and *Mixed*: half of the distractors were presented to the dominant and half through the non-dominant eye. If the pop-out system has information concerning the eye of origin for perceiving individual elements, one would expect the best performance for target presented to the dominant eye and the surrounding elements presented to the opposite eye, so that there is the greatest difference between them.

Previous studies suggested that the most important elements for determining pop-out may be those that are nearest-neighbors to the target (Nothdurft, 1992; Sagi & Julesz, 1987). Therefore, in Experiment 2, we set only the 8 elements that are nearest neighbors to the target to be the Same or Opposite as the eye viewing the target—leaving the other distractors randomly mixed between dominant and non-dominant eye presentation. In this way we wished to compare performance for the cases where all the elements were controlled to those where more distant elements were presented randomly to each eye.[1]

2. General methods

2.1. Subjects

Twenty one subjects performed the experiments: 10 subjects participated in Experiment 1 (8 women and 2 men; 19–56 years of age; median age 25 years) and 13 in Experiment 2 (10 women—2 of whom participated also in Experiment 1—and 3 men; 22–57 years of age; median age 25 years). They were compensated for participation. Visual acuities (VA; Snellen Chart for Far Vision and Rosenbaum Pocket Vision Screener for Near Vision) were tested for each subject, and only those with normal or corrected-to-normal vision (20/20 or better; j1+) and similar VA in their two eyes (same chart line), participated in the experiment.[2]

2.2. Eye dominance

Dominant eye was determined several times, using the Hole-in-the-Card test (Durand & Gould, 1910). Each subject held a black card (20.5×11.0 cm) with both hands outstretched straight forward for a distant target and, for Experiment 1, with their elbows on the desk for a near target, and sighted the target through a hole in the card (3 cm diameter for distance target; 1 cm for near target). Targets were a red circle (of 5 cm diameter at 2.5 m distance) and a cross (1×1 cm at 57 cm distance). When the target was sighted, the examiner covered alternately each of the subject's eyes, and asked if the target was still visible. The eye with which the subject viewed the target was the dominant sighting eye. Using the dependable Hole in the Card Test with these precautions (see Section 1), we found that all subjects had consistent results with the Hole-in-the-Card test. Thirteen subjects (2 males) were found to have a right dominant eye, and 8 (3 males) a left dominant eye. Data for the right and left dominance groups are combined for this study.

2.3. Apparatus and stimuli

Visual stimuli were presented on a 17-in. PC computer monitor placed 57 cm from the subject (75 Hz refresh rate; 1024×768 pixel resolution). Using red–green glasses, subjects viewed a briefly presented 8×8 array of lines, oriented at 60° and pseudo-randomly colored green (RGB: 0, 224, 0) or red (RGB: 224, 0, 0). Screen background was gray (RGB:215, 215, 215). Line colors were chosen so that through the red–green glasses one eye saw only the red and the other only the green lines. Both were perceived as black on a gray background. Lines were $1° \times 0.1°$ and were positioned on the array (at an average line-to-line distance of 1.5° horizontally and 1.0° vertically) with a random positional jitter of up to 3 pixels horizontal and 6 pixels vertical. In addition, in order to help fusion, each array was within a black frame (11.8 cm width $\times$ 8.9 cm height and 0.35 cm thick; RGB: 0, 0, 0), which was presented to both eyes. Stimuli were tested with a photometer (United Detector Technology type 61 Optometer) and brightness was found to be similar through the red and green lenses: 13.2 and 13.5 candles/m^2, respectively. Thus, some of the lines were presented to the left eye and some to the right eye, and we could test for differences in performance when subjects detected the target with the dominant vs. the non-dominant eye. As expected for generally limited utrocular discrimination (see above), subjects were unaware of the eye through which they viewed the target.

On some trials, a red or green line oriented at 40°—i.e. the target—replaced one of the central 36 (6×6) elements. The distractor elements had the same color as the target ("Same"), the opposite color ("Opposite"), or a mixture of the two colors ("Mixed"), as demonstrated in Fig. 1. The main difference between the two experiments was that in Experiment 2 most of the distractors (55 of 63–64) were pseudo-randomly set as red or green, with only the 8 nearest neighbors surrounding the target having the same color as the target (Same), the opposite color (Opposite), or a mixture of four each of the two colors (Mixed). Note that in Experiment 2, when the ring of 8 elements surrounding the target were set as one color, the other 55 elements were set so that half of the total array was red and half green, i.e. 32 elements were presented to each eye (see Fig. 1, right).

2.4. Procedure

Subjects viewed a fixation cross (length/width 0.6°, thickness 0.1°) followed by the stimulus, after a random delay of 150–350 ms (in 50 ms steps). Stimuli appeared for a variable duration of 52, 78, 104, 130, 156 or 182 ms, followed by a 180 ms-duration masking stimulus (an 8×8 array of small asterisk-like elements, each composed of 3 black lines at 60° intervals). Inter-stimulus interval was zero so that stimulus duration equals Stimulus-to-mask Onset Asynchrony as shown schematically in Fig. 2.

Subjects reported presence/absence of an oddly oriented element in the array, by pressing assigned keys on the keyboard ("n" for yes and "v" for no). Correct responses were positively reinforced by a pleasant sound. Half of the subjects started viewing the experiment with the red filter on their right eye and green on their left eye (5 in Experiment 1; 7 in Experiment 2), while the others ($n = 5, 6$) started with oppositely oriented glasses. When subject reached the middle of the experiment (216 trials), they flipped the glasses. No significant difference was found between subjects who began the experiment with the different glasses orientation (Experiment 1: $p = .45$; Experiment 2: $p = .08$).

[1] Preliminary reports of parts of this study have been reported in conference proceeding form (Shneor & Hochstein, 2005a, 2005b).

[2] Note that Experiment 2 was carried out before Experiment 1.

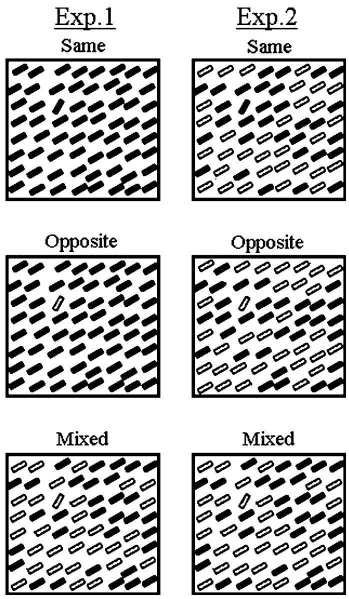

Fig. 1. Schematic demonstration of visual stimuli. The test stimulus was an 8×8 array of lines, oriented at 60° and pseudo-randomly colored green or red so that they were presented to only one eye when viewed through red-green glasses. In the figure, filled and empty bars represent red and green lines, respectively—or vice versa. Each array was within a black frame, presented to both eyes. On some trials, a red or green line oriented at 40°—the target—replaced one of the central (6×6) elements. Distractor elements had the same color as the target in the "Same" condition, the opposite color in the "Opposite" condition, or were a pseudo-random mixture of the two colors in the "Mixed" condition. For Experiment 1 (left column) the full surround obeyed these conditions. For Experiment 2 (right column) only the ring of 8 nearest neighbors to the target were set as same or opposite, with the other, more distant distractors always being mixed so that overall the distractors were half-half red and green.

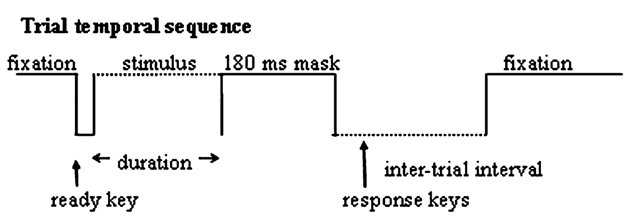

Fig. 2. Trial temporal sequence. Subjects viewed a fixation cross followed by the test stimulus after a random delay of 150–350 ms. Test stimuli appeared for a variable duration of 52–182 ms, followed by a 180 ms duration masking stimulus. There was no delay between the stimulus and the mask, so that stimulus duration equals Stimulus-mask Onset Asynchrony (SOA).

2.5. Trials

Experiment 1 included 432 trials, divided into 3 clusters of 144 trials, each. Each cluster was divided into 3 blocks of 48 trials, within which the type of the stimulus—same, opposite or mixed—was kept constant. These 48 trials were divided equally into trials with or without a target, with the target, when present, being presented in random sequence to the dominant or the non-dominant eye. The distractors were presented randomly either to only the dominant or the non-dominant eye (in same or opposite trials) or half-half (in mixed trials). The 48 stimuli were divided into 6 sub-blocks of fixed stimulus duration. In the first block of the first cluster, stimulus-duration sub-blocks were in a fixed order (182 ms, 130 ms, 78 ms, 156 ms, 104 ms, 52 ms); for the other clusters, the duration sub-blocks were in random order.

In Experiment 2, the 432 trials were divided into 6 clusters, each containing 6 sub-blocks of fixed stimulus duration. Each sub-block contained 12 trials, divided equally into trials with or without a target, with the target, when present, being presented in random sequence to the dominant or the non-dominant eye. The 12 trials were also divided equally among the 3 stimulus types—same, opposite or mixed. Trials without a target were always presented to both eyes, belonging to "mixed" type.

Before beginning Experiment 2, subjects performed 24 training trials divided into 2 blocks of 12 trials with long stimulus durations (390, 260 ms) and divided equally among trials with/without a target; presented to the dominant/non-dominant eye; and with distractors of the 3 stimulus types. Our experience with Experiment 2 led us to cancel this unnecessary training stage of the task.[2]

3. Results

3.1. Performance and detectability

We found better performance for detecting the odd element with the dominant eye than with the non-dominant eye, as demonstrated in Fig. 3, top. Superior performance with the dominant eye is especially pronounced for intermediate stimulus durations (78–104 ms). For this figure, results were averaged across 10 subjects and the 3 stimulation types (see Section 2). Note that performance at the very short stimulus duration (52 ms) was near chance level—50% for this detection task. A four-way ANOVA (without the 52 ms point, in this and following analyses) showed significant main effects for eye dominance, surround type, stimulus duration and subject, as demonstrated in Table 1. We included subject as a main factor in the ANOVA, since we expected that there might be differences in degree of eye dominance in different subjects. Indeed, the

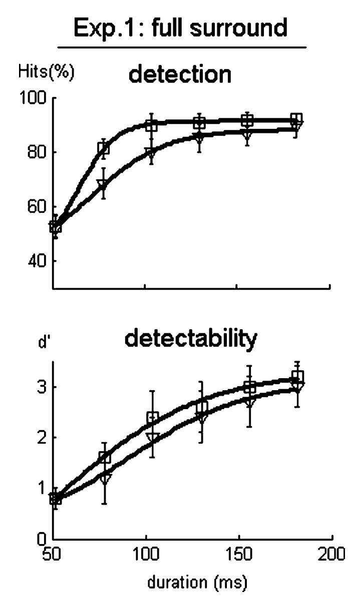

Fig. 3. Detection and detectability in visual search; Experiment 1—full surround. Percent correct detection of the odd orientation target (top) and Signal Detection Theory detectability (bottom) as a function of stimulus duration and eye viewing the target (Dominant eye—squares; non-dominant eye—triangles). Performance (by either measure) is superior when the target is viewed by the dominant eye—especially for middle-duration stimuli.

Table 1
ANOVA for detection and detectability

	Experiment 1				Experiment 2			
	Detection		d'		Detection		d'	
	F	p	F	p	F	p	F	p
Dominance	17.91	<.0001	10.94	<.002	8.37	<.005	9.04	<.003
Type	3.41	<.04	9.35	<.0002	0.89	=.41	1.33	=.27
Duration	12.11	<.0001	27.68	<.0001	39.86	<.0001	70.74	<.0001
Subjects	10.94	<.0001	20.94	<.0001	15.87	<.0001	44.38	<.0001

only interaction terms that were significant were subject * dominance ($F = 7.08$; $p < .001$) and subject * type ($F = 2.74$; $p < .0005$), reflecting different degrees of eye dominance and surround type effects in different subjects.

We also computed the detectability, d', of the odd-element target, taking into account responses for target absent trials (Green & Swets, 1966, 1974). The lower graph of Fig. 3 demonstrates detectability results as a function of stimulus duration for target presented to the dominant or non-dominant eye, respectively. An ANOVA on the detectability data again shows significant main effects (as shown in Table 1) for all main parameters: eye dominance, surround type, stimulus duration and subject. Significant interaction terms were subject * dominance ($F = 3.09$; $p < .002$) and subject * type ($F = 2.03$; $p < .01$), again reflecting different degrees of effect of these factors for different subjects.

3.2. Sigmoid function

Plots of detection or detectability vs. duration (Fig. 3, top and bottom) are sigmoidal. We found the best-fit sigmoid for the across-subject average data, separately, for detection and detectability, and with the dominant and non-dominant eye. As might be expected from the sigmoidal shape, the main difference between the dominant and non-dominant eye lies in the central part of the curve and not in the zero baseline level, and only slightly in the asymptotic ceiling level.

We derived the parameters of the best-fit sigmoid curves, as follows:

$$\text{Performance} = P_0 + (P_\infty - P_0)/[1 + \exp(-k(d - d_\text{m})],$$

where d is the stimulus duration, P_0 and P_∞ are the asymptotic performances for very short and very long durations, respectively; d_m is the stimulus duration giving performance halfway between P_0 and P_∞; and k is the slope at d_m. As is clear from the graphs, the main difference between the best-fit parameters for the dominant vs. non-dominant eye was in k (detection: 1.2 vs. 0.61%/ms; d': 0.032 vs. 0.024/ms) and d_m (detection: 64 vs. 72 ms; d': 55 vs. 92 ms). That is, the effect of eye dominance was in the rate of increasing performance and the stimulation duration where this increase occurred, rather than, for example, in asymptotic performance, P_∞ (detection: 91 vs. 88; d': 3.3 vs. 3.1). P_0 was always close to 50% Hits and $d' < 1$; that is, subjects had some sense of target presence and had fewer False Alarms (average 25%) than Hits, irrespective of the eye to which the target was presented.

3.3. Effect for each type of surround

As discussed in Section 1, we used red–green glasses to control not only the eye through which the target was viewed, but also the eye to which the surrounding distractor elements were presented. We tested 3 conditions, Same, Opposite and Mixed, with the surrounding elements presented, respectively, to the same or the opposite eye as the target, or half to each (Mixed). We report first the effects of this surround type on the difference between the cases where the target was presented to the dominant vs. the non-dominant eye, and refer below to the effect of surround type itself.

Fig. 4 shows that for each type of surround, dominant eye detection and detectability were better than with the non-dominant eye. However, this dependence on eye dominance was greatest with distractors presented to the opposite eye as that seeing the target. These results were confirmed by testing dominance effects for each surround type, by performing an ANOVA for each type, separately, as shown in Table 2. We found main effects for stimulus duration and subject (in all three surround conditions and for both detection and detectability). Significant interaction terms were dominance * subject (detection: Same: $F = 3.68$; $p < .005$, Opposite: $F = 6.43$; $p < .0001$, detectability: Opposite: $F = 3.00$; $p < 0.01$) and stimulus duration * subject (detection: Mixed: $F = 1.89$; $p < .05$, detectability: Mixed: $F = 6.05$; $p < .0001$), demonstrating across-subject variability. More importantly, a significant main effect for eye dominance was found for all three surround types for detection, but only for the opposite case for detectability. This means that while there was a range of more Hits with the dominant eye for each surround type, this increase in Hits came at the expense of a concomitant increase in False Alarms for the same and mixed surround types, and led to a real gain in detectability only for the opposite surround case.

Note that in the Opposite case the target would be the only element viewed by one eye. If the visual system could make use of this information (i.e. the ocular source of the signal) then ocularity itself would lead to pop-out. However, it is well known that utrocular information is not available, and cannot be used by itself for visual search (Wolfe &

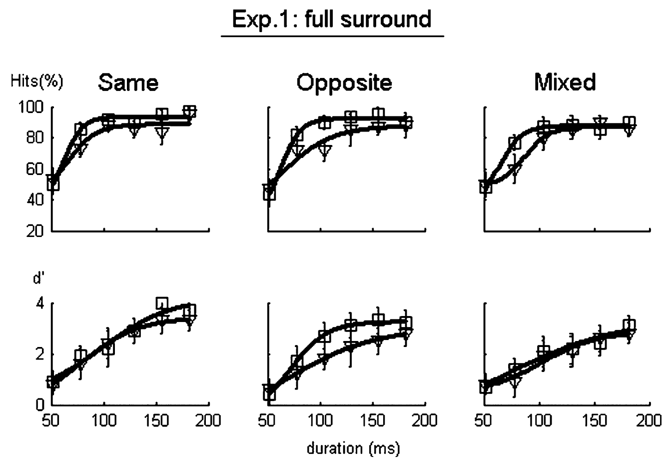

Fig. 4. Detection and detectability for each surround type; Experiment 1—full surround. Percent correct detection of the odd orientation target (top row) and detectability (bottom row) as a function of stimulus duration, surround type (columns), and eye viewing the target (Dominant eye—squares; non-dominant eye—triangles). For each type of surround, the dominant eye performs better than the non-dominant eye, but this dominant-eye advantage is more apparent for the opposite surround case.

Franzel, 1988). The difference between the two cases, target presented to dominant vs. non-dominant eye and all distractors to the other eye, supports the notion that the eye of origin is not a feature supporting feature search, and suggests, instead, that ocularity only adds salience to the target—and does so especially when the target is presented to the dominant eye (for salience or activation level, see the guided search model of Nothdurft (2002) and Wolfe (1994)). This added salience may also be seen as due to inter-ocular masking, with larger distractor-to-target masking when the distractors are presented to the dominant eye.

Note that in the Same condition, the task reduces to a monocular task, with either the dominant or the non-dominant eye. On the other hand, in the Mixed condition, there is always an added noise in the stimulus, in that both eyes are stimulated by the surround distractors, and the task is not only to find the odd orientation, but also to disregard this difference in eye of origin. The graphs of Fig. 4 show a greater difference between dominant and non-dominant eye for detection than for detectability in both the Same and Mixed conditions. This means that the detection difference (in number of Hits) is not reflected in an equal difference in False Alarms for these conditions.

We now ask if the dominance effect found above—as shown in Fig. 3—is present *equally* for each of the three stimulus surround types, or if it is mainly found for one or two of these stimulus types. The ANOVA above already showed that there is a significant main effect for surround type, suggesting a difference between the different types. On the other hand, the cross term for dominance * type was not significant (detection: $F = 0.24$, $p = .79$; d': $F = 2.63$, $p = .074$), suggesting that the difference between the types did not affect the dominance effect. Indeed, the separate ANOVA for each type showed a main dominance effect for all surround types for detection, though only for the opposite case for detectability. As pointed out above, this could mean that the criterion was different for dominant and non-dominant eye detection (for the Same and Mixed conditions) and a detectability difference only for the Opposite case.

Analyzing the data differently, we look at average detection and detectability when the target was presented to the dominant eye, for the three types: Same: 92%; 2.90, Opposite: 90%; 2.77, and Mixed: 85%; 2.21, respectively. When the target was presented to the non-dominant eye these were: Same: 85%; 2.68, Opposite: 81%; 2.10, and Mixed: 80%; 2.04, respectively. Post-hoc t-tests showed that the difference between dominant vs. non-dominant eye detectability were significantly greater for the Opposite type than for either the same ($p < .03$) or mixed ($p < .02$) conditions. This reflects the significant difference between detectability with the dominant eye for the Mixed case (compared to Same: $p < .005$; Opposite: $p < .001$) and with the non-dominant eye for the Same case (compared to Opposite: $p < .02$; Mixed: $p < .005$).

3.4. Extent of the effective surround

Having found that the relative eye viewing the surround distractors is important in determining the speed of the pop-out effect, we now ask what the visual field extent is of the surround that is effective in this regard. Is the entire surround important or, at the other extreme, are only the nearest neighbors to the target important in determining its salience? Previous studies suggested that perhaps only

Table 2
Experiment 1: ANOVA for each surround type

	Same		Opposite		Mixed	
	F	*p*	*F*	*p*	*F*	*p*
Dominance						
Detection	0.93	<.003	7.19	<.02	4.42	<.05
d'	0.60	=.44	17.62	<.0002	3.83	=.06
Duration						
Detection	4.01	<.01	4.17	<.008	8.34	<.0001
d'	7.62	<.0002	10.02	<.0001	36.04	<.0001
Subjects						
Detection	2.20	<.05	7.01	<.0001	10.17	<.0001
d'	4.09	<.0011	11.84	<.0001	34.49	<.0001

a limited area of surround may be important (Nothdurft, 1985, 1992; Sagi & Julesz, 1987). For example, Nothdurft (1992) found that only target elements with high *local* orientation contrast were detected fast and "in parallel". However, to our knowledge, no previous study has addressed this issue in terms of the eye viewing the target and the surrounding distractors. As a first indication, we asked subjects to find the orientation target when the distractors were divided half-half between the two eyes, and only a ring of the 8 neighbors to the target were set to be either all viewed by the Same or the Opposite eye as the target—or here, too, mixed half-half.

In this experiment, as in the previous experiment, we found better detection and larger d' for viewing the odd element with the dominant eye than with the non-dominant eye, as demonstrated in Fig. 5. A four way ANOVA showed significant main effects for eye dominance (detection: $F = 8.37$; $p < .005$; d': $F = 9.04$; $p < .005$), subject (detection: $F = 15.87$; $p < .0001$; d': $F = 44.38$; $p < .0001$), stimulus duration (detection: $F = 39.86$; $p < .0001$; d': $F = 70.74$; $p < .0001$). The only significant interactions term were subject $*$ stimulus duration (detection: $F = 2.12$; $p < .0001$; d': $F = 2.49$; $p < 0.0001$), reflecting different response functions in different subjects, and dominance $*$ subject (detection: $F = 1.87$; $p < .05$; d': $F = 1.87$; $p < .05$)

Interestingly, the main dominance effects seen in the plots of detection and d' dependence on duration are seen at long durations, where detection and d' approach eye-dominance dependent asymptotes. Therefore, we performed an ANOVA, taking into account only the three longest durations. As expected, the detection duration effect disappeared (since we are at ceiling; $F = 1.08$; $p = 0.34$; though the effect is significant for detectability: $F = 7.65$; $p < .001$), leaving significant main effects for subject (detection: $F = 6.92$; $p < .0001$; d': $F = 22.74$; $p < .0001$) and an even more significant effect for eye dominance than found in the preceding paragraph with all durations (detection: $F = 15.86$; $p < .0002$; d': $F = 11.10$; $p < .002$).

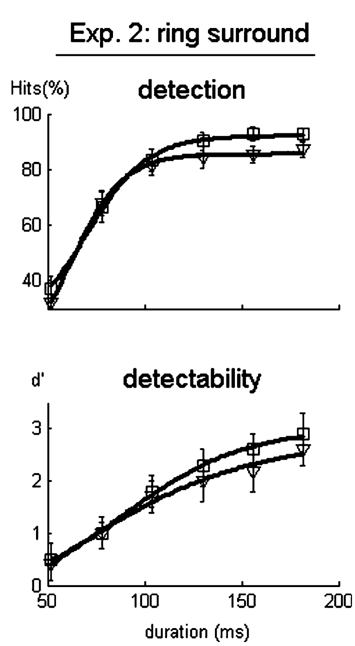

Fig. 5. Detection and detectability in visual search; Experiment 2—ring surround. Percent correct detection of the odd orientation target (top) and detectability (bottom) as a function of stimulus duration and eye viewing the target (Dominant eye—squares; non-dominant eye—triangles). Performance (by either measure) is superior when the target is viewed by the dominant eye—especially for long-duration stimuli.

As in Experiment 1, we fit the psychometric curves to sigmoid functions, drawn as the solid lines of Fig. 5, and derived the parameters of the best-fit curve in each case. As mentioned above, the main consistent difference between the parameters for the cases with the target presented to the dominant and non-dominant eye was in the high stimulus duration asymptote. This result suggests the surprising conclusion that the eye-dominance effect (when the distractors were presented half-half to the two eyes) was not simply a relative advantage of one eye over the other, such as a reduced processing time or an increased salience, which we would have expected to result in a difference in the effective stimulus duration, or a shift in the curve along the *x*- (stimulus duration) axis. Instead, the effect seems to derive specifically from the interaction between the eyes, competition between them or mutual inhibition. This interaction may grow rather than be diminished with increasing processing time; (e.g. Wolfe (1986) suggested that in the first 200 ms there is always binocular integration rather than rivalry). This interaction leads to poorer performance for the non-dominant eye when in a competitive situation even when the signal is so large (stimulus duration so long) that without the competition, there would be no problem with performing the task perfectly with the non-dominant eye.

The main difference between the best-fit parameters for the dominant vs. non-dominant eye was in P_∞ (detection: 92 vs. 86; d': 3.015 vs. 2.83), rather than in k (1.14 vs. 1.48; 0.026 vs. 0.025), d_m (70 vs. 61 ms; 91 vs. 52 ms), or, alternatively, in the duration required for reaching a fixed threshold. We also computed the best-fit curves for each subject and each eye, and performed an ANOVA on these data. Once again, the only consistent difference between the dominant and non-dominant eye parameters was in the high-duration asymptote P_∞ (detection: $F = 10.98$; $p < .01$; d': $F = 5.49$; $p < .05$). This surprising result suggests that the dominant eye effect on task performance derives from competition between the eyes, as discussed below.

Fig. 6 demonstrates separate results for the three stimulus types, Same, Opposite and Mixed, and Table 3 shows the ANOVA results for each type. Again, the dominant eye performs better than the non-dominant eye for all surrounds types. Note that the eye dominance effect was significant only for the Opposite condition. The only significant interaction term was subject $*$ stimulus duration (detection: Mixed: $F = 1.6687$; $p < .04$).

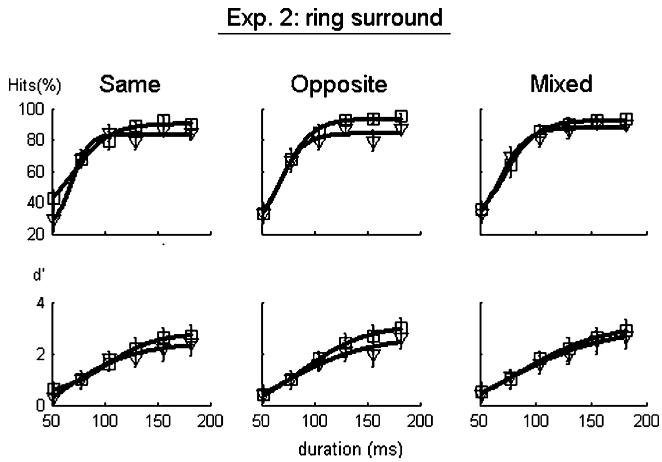

Fig. 6. Detection and detectability for each surround type; Experiment 2—ring surround. Percent correct detection of the odd orientation target (top row) and detectability (bottom row) as a function of stimulus duration, surround type (columns), and eye viewing the target (Dominant eye—squares; non-dominant eye—triangles). For each type of surround, the dominant eye performs better than the non-dominant eye, but this dominant-eye advantage is more apparent for the opposite surround case.

3.5. Comparison between Experiments 1 and 2, and the dominance index

It has been shown that detection of an oddly oriented element depends on local orientation gradients (Nothdurft, 1985, 1991, 1992; Sagi & Julesz, 1987). Thus, the most important elements for determining pop-out should be those in a ring around the target, i.e., the nearest-neighbors to the target (Sagi & Julesz, 1987). In the context of our study of the effects of eye dominance, we compared the effects of setting the full surround or only a ring around the target to be presented to the same or the opposite eye as the target.

We found in Experiment 1 that detection of an odd element depends on the eye to which all the surrounding elements were presented. Furthermore, a significant difference was seen between the results of the 2 experiments, with performance improving when a larger proportion of the distractors were presented to the same eye. We conclude that regarding viewing eye, detection does not depend only on local differences but is influenced also by the more distant elements, perhaps even the entire array.

As a tool for comparing the 2 experiments, we define a Dominance Index (in percent), as

$$\mathrm{DI} = 100 \times [P(d) - P(n)]/[P(d) + P(n)]$$

where, P is the performance (% correct or d'); d is the dominant eye; n is the non-dominant eye.

We plot DI for Experiments 1 and 2, for detection and detectability in Fig. 7, and for each surround type in Fig. 8. DI is larger for Experiment 2 with full surround, than for Experiment 1 with ring surround, and larger for Opposite than Same or Mixed type.

We also tested performance and DI for detection and detectability as a function of stimulus duration. Fig. 9 demonstrates that the DI is nearly constant, and nearly the same for full and for ring surround, at long stimulus durations ($\geqslant$130 ms). At short durations, DI is higher and gradually declines with duration for the full surround (reflecting the decreasing gap between dominant and non-dominant eye performance), and low and gradually increasing for ring surround (reflecting the general increase in performance).

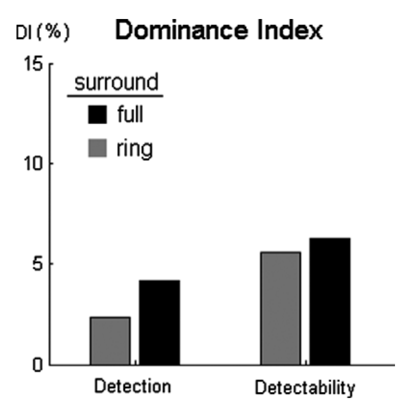

Fig. 7. Dominance index for detection and detectability. Dominance Index for detection (left bars) and detectability (right bars). Note that the Dominance Index is higher for Experiment 1 (full surround; black) than for Experiment 2 (ring surround; gray).

Table 3
Experiment 2: ANOVA for each surround type

	Same		Opposite		Mixed	
	F	*p*	*F*	*p*	*F*	*p*
Dominance						
Detection	1.52	=.222	6.92	<.02	0.72	=.4004
d'	2.14	=.150	4.77	<.05	1.18	=.283
Duration						
Detection	8.97	<.0001	11.47	<.0001	20.44	<.0001
d'	16.11	<.0001	18.48	<.0001	27.44	<.0001
Subjects						
Detection	3.47	<.002	6.20	<.0001	8.86	<.0001
d'	11.75	<.0001	11.33	<.0001	17.31	<.0001

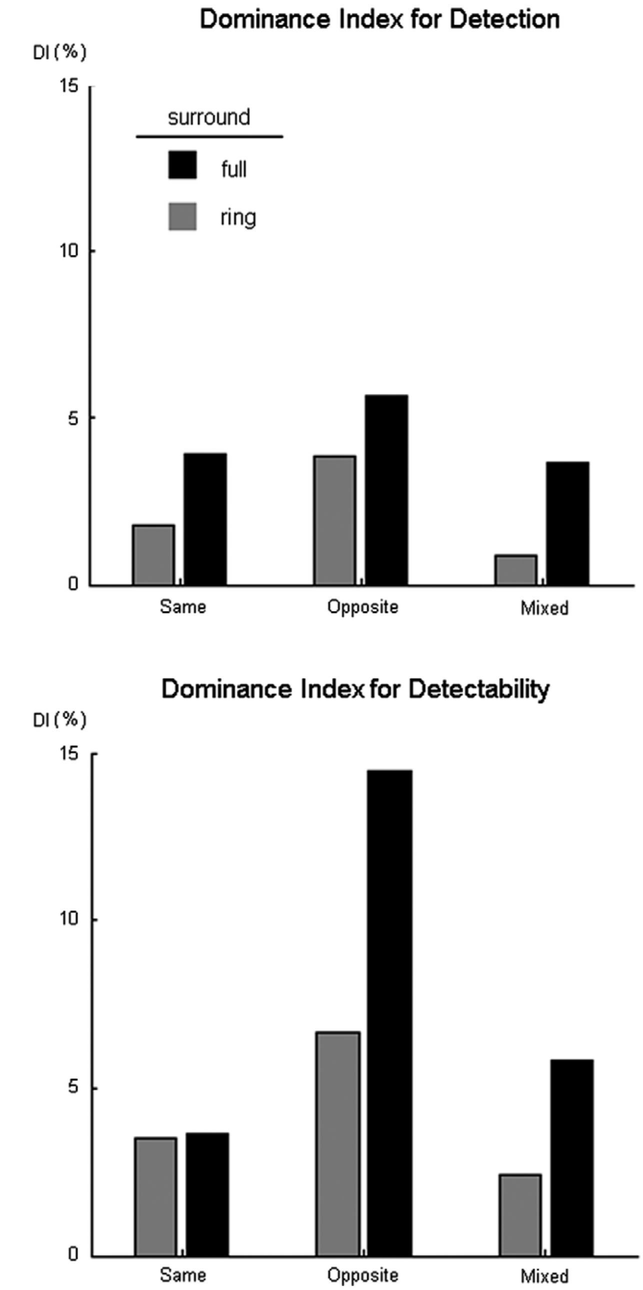

Fig. 8. Dominance index for detection and detectability for each surround type. Dominance Index for detection (top) and detectability (bottom) is presented separately for same, opposite or mixed surround types, and for Experiment 1 (full surround; black bars) and Experiment 2 (ring surround; gray bars). Note that the Dominance Index is greatest for the Opposite case, and greater for Experiment 1 than for Experiment 2. Thus, performance is affected by the eye viewing the surround, not only for the nearest neighbors to the target, but also for elements much further away.

A 3-way ANOVA showed significant main effects for difference between the two experiments (using all 6 durations; detection: $F = 16.78$, $p < .0002$; d': $F = 43.29$, $p < .0001$; an expected larger dominance effect when the surround includes the entire array than when it includes only the ring around the target), stimulus duration (detection: $F = 224.38$, $p < .0001$; d': $F = 121.39$, $p < .0001$) and

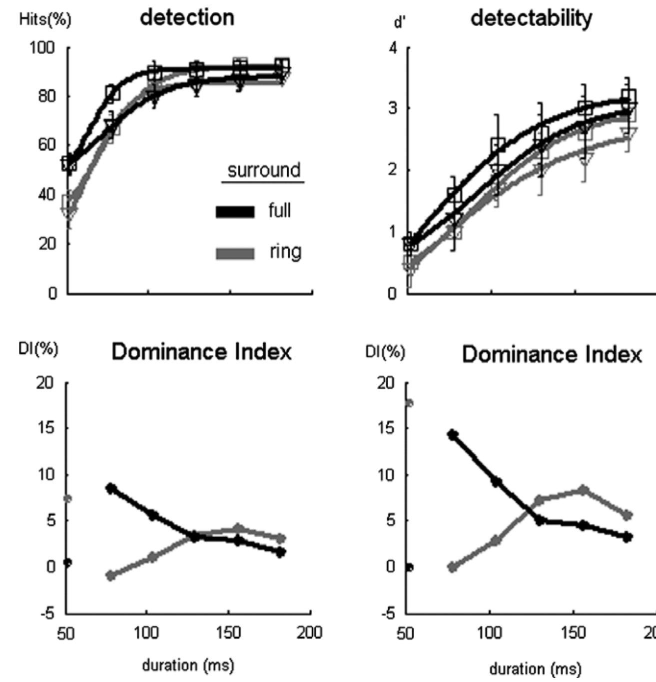

Fig. 9. Dominance index for detection and detectability as a function of stimulus duration. The results of Figs. 3 and 5 are superimposed (top row) to facilitate comparison of results and eye-dominance effects for full vs. ring surround. Detection (left) and detectability (right) are higher for Experiment 1 (full surround; black lines) than for Experiment 2 (ring surround; gray line). The Dominance Index is nearly constant and nearly the same for full and for ring surround, at long stimulus durations ($\geqslant 130$ ms). At short durations, the Dominance Index is higher and gradually declines with duration for the full surround (reflecting the decreasing gap between dominant and non-dominant eye performance), and low and increasing for ring surround (reflecting the general increase in performance).

dominance (detection: $F = 21.64$, $p < .0001$; d': $F = 13.09$, $p < 0.001$).

Performing a separate ANOVA for detectability with each surround type, we find significant main effects for full vs. ring surround for same and opposite types (Same: $F = 201.91$, $p < .0001$; Opposite: $F = 28.75$, $p < .005$) and for eye dominance (Same: $F = 13.412$, $p < .02$; Opposite: $F = 31.30$, $p < 0.003$).

In conclusion, we found that detection of an odd element depends on the eye that sees the target and the surrounding elements—and on the extent of this uniform surround. We conclude that regarding viewing eye, detection does not depend only on local differences but is influenced also by more distant elements, perhaps even the entire array.

4. Discussion

We found that performance was better using the dominant eye, suggesting that this eye may have priority in visual processing. It is well known that when there is direct competition between the two eyes, the dominant eye takes over more frequently—as in binocular rivalry or various sighting tests, including the hole-in-the-card test, used by us to determine which is the dominant eye. We now find that even when there is no direct competition, and where the brain could easily use the information from the two eyes in a complementary fashion to form a single complete picture, nevertheless, there is an advantage to information gathered by the dominant eye. Note that the subjects were not aware of the ocular source of the visual information used to detect the target. Still they performed better when the target was presented to the dominant eye. Furthermore, performance depended on the eye to which the surround distractor elements were presented, including elements more distant than the immediately neighboring elements. These effects must be seen as interplay between implicit ocularity information and explicit perception of stimulus orientation.

We argue that a target which is presented to the dominant eye may be more salient than a target which is presented to the non-dominant eye, so that it is easier to detect this more salient target. Thus, in the Same condition, which mimics the general case of visual search (except that it is transformed to a monocular task), performance is better when the target (as the distractors) is presented to the dominant eye. This salience difference may also lead to faster processing of the visual information arriving from the dominant eye (Coren & Porac, 1982; Minucci & Conners, 1964; Money, 1972; Porac & Coren, 1979; Sampson & Spong, 1962). Faster processing in our case is measured by better performance for the same stimulus durations (a rightward shift of the sigmoid psychometric curve). Another alternative is that there are more cortical neurons representing information arriving from the dominant eye (Porac & Coren, 1982), again leading to better or faster performance for a target that has a broader representation. In summary, the dominant eye seems to be the better or stronger eye in the sense that its signals are more salient, due to greater strength and/or larger neuronal population in its representation.

When detection was tested as a function of eye dominance of surrounding elements, we found that in all 3 conditions (Same, Opposite and Mixed) there was better performance for target presented to the dominant eye. In addition, the largest and most significant difference between performance with the target presented to the dominant vs. the non-dominant eye was obtained when the target was presented to one eye, and the surrounding elements were presented to the other (i.e. the Opposite condition). These results are indicative of the mechanism underlying pop-out. Presumably, pop-out depends on the difference between the target and the distractor elements. The major, determining, difference between the target and the distractors is, of course, their orientations. It would seem, however, that the eye viewing the target vs. the distractor elements is another such differentiating factor. Yet, there is a required order to this difference, determining if it is to assist or rather counteract pop-out, as follows: If the difference adds to the salience of the target element—e.g. by viewing the target through the dominant eye and the distractors by the non-dominant eye—then the target more easily pops out. However, if the target is viewed by the non-dominant eye and the surrounding distractors by the dominant eye, then perhaps a reverse salience is introduced and performance drops. There is clear evidence for both these effects: (1) If the surround is presented to the non-dominant eye, performance is better (post-hoc *t*-test: $p < .05$) if the target is presented to the dominant eye (Opposite case; dominant eye) than to the non-dominant eye (Same case, non-dominant eye). Similarly, (2) if the surround elements are presented to the dominant eye, then performance is better ($p < .005$) if the target is also presented to the dominant eye (Same case, dominant eye), than if the target is presented to the non-dominant eye (Opposite case, non-dominant eye). Once again, recall that these ocularity effects are implicit and subjects are not aware that some elements are presented to the dominant and some to the non-dominant eye.

Considering the surround elements, the effects are somewhat different. The surround elements are to be ignored, and it has been suggested that lateral inhibition among the elements representing the different surround elements may play a role in this depression of their signals (Knierim & Van Essen, 1992). If lateral inhibition depends on stimulus similarity, we would expect more inhibition (and thus better pop-out) when all the surround elements have the same orientation (as is the case for all our experiments) and when they are presented to the same eye—as is the case for either the same or the opposite cases but not the mixed case. Indeed, we found that for target presentation to the dominant eye, performance is superior when the surround elements are all presented to either the dominant (detection: $p < .005$; d': $p < .005$) or the non-dominant (detection: $p < 0.05$: d': $p < .001$) eye, compared to the Mixed case, when half are presented to one eye and half to the other. Interestingly, when the target is presented to the non-dominant eye, pop-out is sufficiently weak that there is not much difference between the cases when the surround is presented to one eye (Same or Opposite cases) or to both eyes (Mixed case). Nevertheless, detectability is greater when none of the surround elements are presented to the dominant eye (i.e. non-dominant eye, Same vs. Mixed: $p < .005$; Same vs. Opposite: $p < .02$).

There is an additional factor, however, when considering the impact of which eye is seeing the target and the surrounding elements: If different eyes see the target and the surround, then there may be direct inhibition of the non-dominant eye representation by the dominant eye representation. That is, even though there is no direct rivalry between them, i.e. there is no conflicting, overlapping, element, nevertheless, the same mechanism that operates when there is direct rivalry, may operate also when the is dichoptic stimulation, though no direct rivalry. This inhibition would be most effective in the case of a target presented to the non-dominant eye when there are surround elements presented to the dominant eye.

In this case, performance would be degraded by the cross-eye inhibition. Indeed, performance is better with a non-dominant eye target for the same case (all distractors presented to the non-dominant eye; no cross-eye inhibition) than for the other two conditions, Mixed or Opposite (half or all of the distractors presented to the dominant eye; detection: $p < .05$; d': $p < 0.005$), supporting the conclusion that there is indeed inhibition from the dominant eye representation on the non-dominant eye representation when these are both present—even when there is no direct rivalry between them. The fact that this is a non-local interaction suggests that it depends on high-level, large receptive field, mechanisms; (e.g. see Hochstein & Ahissar, 2002).

Comparing Experiment 2 with Experiment 1, we found that the Dominance Index was significantly reduced by limiting the uniform surround to a ring of elements immediately adjacent to the target. This suggests that the interactions between the target and the distractors is not limited to the ring of neighboring elements, but rather is spread to more distant elements. Sagi & Julesz (1987) & Nothdurft (1985, 1991, 1992) found that the distractors that most determine pop-out are the nearest neighbors to the target. Of course, they refer to the orientation of the elements, and their determining an orientation pop-out. In our case, we are dealing with an additional factor, the eye to which the elements are presented in this dichoptic array. While the orientation gradient may be determined more locally, with nearest neighbors having the major impact, cross-eye inhibition may be effective further a field. As suggested above, the large distance over which the interocular interaction takes place suggests a high level mechanism for this eye-dominance effect (Hochstein & Ahissar, 2002).

5. Conclusions

In conclusion, we found better performance in a visual search task for the dominant eye. These results suggest that the dominant eye has perceptual processing priority, arising from enhanced salience of the perceived target. In addition, we found the surprising result that representations of elements presented to the dominant eye inhibit the input that arrives via the non-dominant eye. These results contrast the suggestion made by Mapp et al. (2003) that eye dominance has no effect in performing binocular tasks, but only affects the eye that will be preferred for performing a monocular task. The findings are even more significant when one considers that all potential subjects were screened for eye-dominance using the hole-in-the-card test. That is, we used a monocular, not a competitive binocular test for choosing subjects and determining their dominant eye. Finally, these effects work at long range and thus are probably based on high level mechanisms.

These principles may be used in practice when designing visual displays. If a task is to be performed monocularly (as in looking through a telescope or microscope) then participants should use the dominant eye; (see also Mapp et al., 2003). However, when we can introduce information to both eyes, separately, then superior performance may be obtained by having target information introduced to the dominant eye and non-target, noise, introduced to the other, non-dominant, eye. This may be implemented, for example, by having the viewer identify a target at one moment, and having it presented from then on to the dominant eye while other objects are presented to the non-dominant eye.

Acknowledgments

We thank Anne Treisman for many discussions leading to and concerning this study; Svetlana Lein for help with programming; Gilad Jacobson for help with statistical analysis. This study was supported by a ‘‘Center of Excellence’’ grant from the Israel Science Foundation of the Israel Academy of Sciences and a grant from the US-Israel Bi-national Science Foundation (BSF).

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