



Cortical Components of the Westheimer Function

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The Westheimer function in human cone vision was measured in normal observers under dichoptic conditions and in observers with naturally acquired amblyopia. Results show interocular transfer of both desensitization and sensitization under either "sustained" or "transient" stimulus conditions if binocular rivalry is eliminated. The spatial sensitization branches of the amblyopic functions are considerably broadened as compared with those of the non-amblyopic function. Our results are consistent with cortical components for the Westheimer function which probably reflect the behavior of cortical spatial filters. © 1997 Elsevier Science Ltd

Westheimer function Perceptive field Spatial filter Interocular transfer Amblyopia

INTRODUCTION

When a small spot target is centered on a circular background of various sizes, the detection threshold first increases (desensitization) until reaching a peak, then decreases (sensitization) until reaching an asymptote as the size of the background increases (Crawford, 1940; Westheimer, 1965, 1967). This effect, known as the Westheimer function, is generally interpreted as mirroring the center/surround organization of the retinal cell receptive fields (e.g., Enoch, 1978; Hayhoe, 1979a,b; Spillmann *et al.*, 1987; Westheimer, 1965, 1967), with desensitization matching spatial summation of the excitatory receptive field center, and sensitization matching inhibition of the antagonistic receptive field surround. Support for a retinal origin of the Westheimer function comes from studies comparing properties of psychophysical perceptive fields to properties of ganglion cell receptive fields (e.g., Enoch & Sunga, 1969; Spillmann *et al.*, 1987). For instance, Spillmann *et al.* (1987) reported close agreement between sizes of human perceptive fields and sizes of monkey perceptive fields and ganglion cell receptive fields. More importantly, support also comes from dichoptic and clinical measurements which test the retinal theory more directly.

Dichoptic studies

Westheimer (1967) first examined the dichoptic effect by presenting a spot target and a peak-diameter center disk to one eye of the observer and a concentric annulus equal to the antagonistic surround to the other eye. It was expected that the dichoptically added annulus would lower the threshold if there was any interocular transfer of the sensitization effect. However, the added annulus

did not reduce, but actually slightly elevated the threshold. Similar results were also replicated in later studies (Fiorentini *et al.*, 1972; Sturr & Teller, 1973). Failure to observe interocular transfer of sensitization was explained on the basis that the Westheimer function occurs before the binocular convergence of visual inputs, and thus is organized precortically (Westheimer, 1967).

Dichoptic tests have also been conducted in which the spot target is presented to one eye and the entire background to the other eye. These tests, however, have produced mixed results. Under "transient conditions", i.e., the target and background have the same onset, interocular transfer has been observed (Fiorentini *et al.*, 1972; Sturr & Teller, 1973). Under "steady or sustained conditions", i.e., the background remains constant but the target flashes as in Westheimer's original studies, interocular transfer could not be found by Johnson and Enoch (1976), but was evident in Markoff and Sturr's (1971) experiments. These results were interpreted as suggesting that the transient functions are determined by cortical mechanisms but the sustained functions are determined by retinal mechanisms (Sturr & Teller, 1973). It is unclear why results from dichoptic measurements are not always consistent. Neither is it clear why the transient effects should be interocularly transferred but the sustained effects be limited within the retina. Such a difference is contradicted by neurophysiological findings of parallel sustained and transient retino-cortical pathways (Livingstone & Hubel, 1988). On the other hand, the significant effect of binocular rivalry suppression might play an important role in determining the presence and degree of interocular transfer (Fox & Check, 1966).

Clinical studies

Enoch and his colleagues (e.g., Enoch, 1978; Enoch & Sunga, 1969; Enoch *et al.*, 1985) reported that inner retinal pathology, particularly open-angle glaucoma, altered the Westheimer function, while diseases beyond

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the inner retina and before the LGN, such as retrobulbar optic neuritis and sharp chiasmal lesion caused by tumor, had no effect. These and other findings led Enoch *et al.* to conclude that the Westheimer function is organized at the inner retina outer plexiform layer (see Enoch (1978) for a review). However, in our opinion, although these studies suggest a role for the retina in the organization of the Westheimer function, the conclusion is not exclusive. As Sturr and Teller (1973) suggested, the retinal diseases investigated by Enoch *et al.* would not only disturb the information processing within the retina, but also distort the information passed upstream to the visual cortex. There still exists the possibility that a distorted Westheimer function is the output of cortical processing on distorted input from the diseased retina. Thus, the role of the visual cortex in the Westheimer function cannot be completely excluded before it is directly examined.

Lawwill *et al.* (1973) tested one anisometric amblyopic patient with the Westheimer paradigm and reported a function which had a moderately enlarged desensitization branch and a greatly enlarged sensitization branch. Based on the retinal theory of the Westheimer function, these results were interpreted as indicating a retinal anomaly in the amblyopic visual system (Lawwill, 1978). However, this interpretation has to be questioned based on more recent psychophysical, anatomical, and neurophysiological evidence which suggests that amblyopia primarily affects cortical processes (see Discussion), and their results could be an indication of cortical involvement in the Westheimer function.

In a recent study, Yu and Essock (1996b) examined spatial scaling properties of the Westheimer function across the visual field (at 0, 5 and 10 deg retinal eccentricities). The size of the sensitization branch or antagonistic perceptive field surround showed a rapid increase as a function of the retinal eccentricity. The average E_2 value of the spatial scaling function of sensitization was about 0.88 deg, close to the E_2 value estimated for cortical magnification but significantly different from those of retinal cone or ganglion cell spacing (Levi *et al.*, 1985). A rapid increase of the sensitization range across the visual field was also reported by Ransom-Hogg and Spillmann (1980). These data suggest that sensitization might be limited by cortical factors, in contrast to the common assumption that it is a retinal function. On the other hand, the range of the desensitization branch increased much more slowly across the visual field, with an average E_2 value of 2.35 deg, comparable with E_2 values of cone and ganglion cell spacing, as well as the E_2 value of the center of cortical receptive fields (Levi *et al.*, 1985; Wilson *et al.*, 1990). Thus, the neural locus of desensitization was not determined by spatial scaling measurements.

The spatial scaling results, and other evidence, such as Lawwill and colleagues' amblyopia data (Lawwill *et al.*, 1973), indicate the necessity of revisiting the classical retinal theory of the Westheimer function. In the current

study we measure the Westheimer function dichoptically and in humans with naturally acquired amblyopia. We demonstrate interocular transfer of both desensitization and sensitization under either "sustained" or "transient" stimulus conditions if measurements are not interfered with by binocular rivalry. We also demonstrate that amblyopia alters the Westheimer function in that it moderately broadens the desensitization branch and greatly enlarges the sensitization branch of the function. Taken together, these results suggest that the Westheimer function is more likely a cortical effect, probably reflecting the behavior of cortical spatial filters.

GENERAL METHODS

Observers

Normal observers. Three females aged 19–24 yr served in all dichoptic experiments. One male served in Experiment 3 only. All were slightly myopic and wore appropriate lenses to correct the vision of each eye to 20/20 or better. Their stereopsis, examined with the Randot Stereotest (Stereo Optical Co., Inc., Chicago, IL), was normal (20 sec). They had no prior psychophysical experience and were naïve as to the purpose of the study.

Amblyopic observers. Two amblyopes, highly experienced in psychophysical observations, participated. Observer RH (male, 25 yr) was strabismic, with corrected vision of 20/15 in the preferred eye (O.D.) and 20/68 in the amblyopic eye (O.S.). Observer AJ (female, 26 yr) was strabismic and anisometric, with corrected vision of 20/15 in the preferred eye (O.S.) and 20/60 in the amblyopic eye (O.D.).

Apparatus and stimuli

The stimuli were generated by a Vision Works computer graphics system (Vision Research Graphics, Inc., Durham, NC) and presented on a U.S. Pixel Px19 monochrome monitor (Experiments 1, 2, and 4) or an Image System M21LMax monochrome monitor (Experiment 3). Both monitors had a resolution of 1024×512 pixels. Pixel size was 0.28 mm horizontal \times 0.41 mm vertical. The frame rate was 117 Hz. Luminance of the monitors was made linear by means of an 8-bit look-up table. A pair of twisted nematic liquid-crystal shutter glasses (Experiments 1 and 2) or Ferro-Electric stereo shutter glasses (Experiment 3) was used to control the dichoptic stimulus presentation. The transmission rate was about 10% for the first pair of shutter glasses and about 30% for the second pair. A potential difficulty with using shutter glasses for dichoptic displays is leakage or crosstalk. Measurements of leakage for our system are presented elsewhere (Mussap & Levi, 1995). We tested the possible effects of crosstalk in the present experiments on two observers (CN and RP). A 19' circle (the largest background used in dichoptic experiments) was presented to one occluded eye and the detection rate was measured on the other eye with a 2AFC staircase procedure, with all other conditions matching our experimental conditions (see below). The minimal

luminance required to detect the crosstalk was about four times as high as the background luminance used in the experiments. There was little difference between the results of two observers. Thus, we believe that the crosstalk had little effect on the results we are reporting.

Another potential difficulty with dichoptic measurements is fluctuations in vergence. In order to minimize any effect of vergence fluctuations, fixation disparity was nulled out prior to each trial in Experiments 2 and 3, by using a trackball to properly align the dichoptically presented objects.

The basic stimulus configuration consisted of a foveal spot target of 1.5' diameter centered on a circular background of variable size. Variations in dichoptic viewing conditions are detailed in the descriptions of specific experiments. The luminance of the screen and background field were 6.8 and 23.8 cd/m², respectively, in the dichoptic experiments. These values were then reduced by the shutter-glasses to about 0.68 and 2.38 cd/m², respectively, in Experiments 1 and 2, and about 2.04 and 7.14 cd/m², respectively, in Experiment 3. In amblyopic experiments, these luminance values were 2.5 and 26.7 cd/m², respectively. The luminance of the spot-target was varied according to a staircase procedure. The viewing distance was 5.64 m.

Procedure

A successive two-alternative forced-choice (2AFC) staircase procedure with a convergence rate of 75% was used (except in Experiment 3 where a method of adjustment was used, see Experiment 3 for details). Under sustained conditions, the target with its luminance profile modulated by a temporal gaussian window ($\sigma = 130$ msec) was presented in one of the two intervals (800 msec each) with the same duration. The background was presented 1 sec before the onset of the first interval, and was on constantly until 1 sec after the offset of the second interval. In this way any transient effect due to the background onset and offset could be avoided. The inter-stimulus interval was also 1 sec. Under transient conditions, the background and target had abrupt onset and offset. The background (400 msec) was presented in both stimulus intervals (400 msec each). The latter was separated by a 600 msec blank inter-stimulus interval. The target, also 400 msec, was presented in one of two stimulus intervals. The screen luminance always remained constant both throughout and between trials. Each trial was preceded by a 6.3' \times 6.3' binocular fixation cross in the center of the screen which disappeared 100 msec before the beginning of the trial.

Each staircase consisted of four practice reversals and six experimental reversals. The mean of the six experimental reversals was used to estimate the increment threshold, defined as $\log \Delta L$. A dichoptic experimental session usually consisted of 10 conditions of various background sizes, typically five dichoptic and five monoptic, in a random order, and lasted for about 50 min. An amblyopic test session usually consisted of 14–15 randomly presented conditions, six or seven for

the preferred eye and eight for the amblyopic eye, and lasted for 90 min or less. Each datum represents the mean of five replications for each condition, and the error bars represent ± 1 standard error of the mean (SEM).

EXPERIMENT 1: DICHOPTIC MEASUREMENTS WITH THE TARGET AND BACKGROUND PRESENTED TO DIFFERENT EYES

In this experiment we measured the dichoptic Westheimer function with the spot target presented to one eye and the background to the other eye (dichoptic condition). As a control, the target and background were also presented to the same eye (monoptic condition). The background size was varied at 3, 6, 9, 13 and 19' in diameter. Because different results had been reported with sustained and transient stimulus conditions, both conditions were tested, run in different sessions in a counterbalanced order.

Our results show the inverted-V shapes typical of the Westheimer function under both monoptic and dichoptic conditions (Fig. 1). Both the desensitization and sensitization processes of the Westheimer function can be achieved by dichoptically induced background effects. The dichoptic and monoptic curves, either sustained [Fig. 1(a)] or transient [Fig. 1(b)], peak at the same background diameter (about 9') with only one exception (RP's sustained curves). This close agreement suggests that dichoptic and monoptic functions are probably modulated by the same mechanism.

The 9' peak diameter under both monoptic and dichoptic conditions is larger than the usual 5–6' value seen in many previous experiments. This difference could be caused by the low luminance of the background (2.38 cd/m²) viewed through the shutter glasses. There is evidence suggesting increased size of central summation or receptive field center with low stimulus luminance (Barlow *et al.*, 1957; Crawford, 1940). The peak diameter was back to 6' for preferred eyes in Experiment 4 in which shutter glasses were not used.

The average sensitization effect is about 0.15 and 0.11 log units for dichoptic and monoptic conditions, respectively, which is rather small as compared with Westheimer's original report (about 0.6 log units). This difference can also be attributed to the low luminance of the background, as the sensitization effect decreases as the background luminance decreases (Westheimer, 1967), and the effect is much stronger in Experiment 4 for both amblyopic observers who were tested at a higher background luminance.

The overall dichoptic threshold is higher than the monoptic threshold under both sustained and transient conditions, consistent with Fox and Check's (1966) finding that stimuli presented to one eye tend to raise thresholds in the other eye. Similar effects were also reported in masking experiments in which dichoptic masking was found to be more effective in elevating the test grating threshold than monoptic masking (Legge, 1979; Levi and Harwerth, 1982). This interocular suppression appears to be nonspecific to desensitization

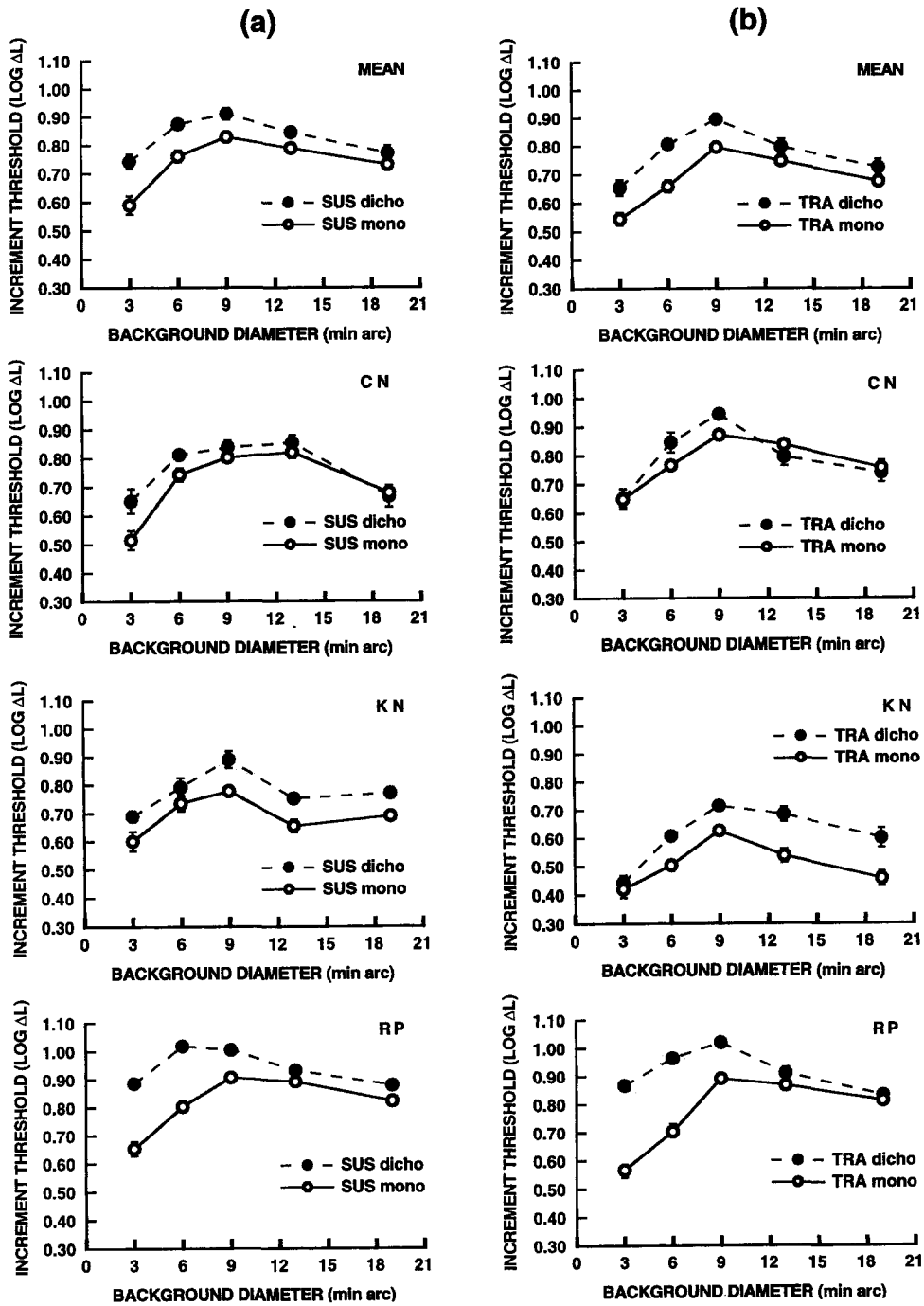


FIGURE 1. Dichoptic and monoptic thresholds as a function of the background diameter. (a) Shows data collected under sustained conditions (labeled as SUS). (b) Shows data collected under transient conditions (labeled as TRA). The top panels show the results averaged across observers (error bars indicate the mean of individual standard errors).

and sensitization in the Westheimer function. However, the same effect was not shown in Johnson and Enoch (1976)'s measurements in which dichoptic thresholds were much lower than monoptic thresholds and presented as flat functions.

Our results also suggest that both sustained and transient stimulus conditions can equally effectively elicit interocular transfer. Although there are relatively large variations between sustained and transient dichoptic functions within each observer, the mean curves are very similar to each other, suggesting that both conditions influence interocular transfer in a similar way. This

conclusion is further supported by evidence from amblyopia experiments (Experiment 4).

EXPERIMENT 2: DICHOPTIC MEASUREMENTS WITH THE TARGET AND CENTER DISK TO ONE EYE AND THE SURROUNDING ANNULUS TO THE OTHER EYE

When the target and peak-diameter center disk are presented to one eye and the surrounding annulus to the other eye, thresholds are consistently equal to or higher than those measured under the center-disk-only condition

(Fiorentini *et al.*, 1972; Sturr & Teller, 1973; Westheimer, 1967). These results have been used as a cornerstone to support the retinal theory of the Westheimer function. However, they are not consistent with the results of Experiment 1. In this experiment we tried to resolve this apparent inconsistency.

We first performed this dichoptic annulus experiment with the same three observers. The center disk diameter and the inner diameter of the annulus were both 9', the peak diameter found in Experiment 1. The outer diameter of the annulus was 19'. The average ocular misalignment of the annulus and center disk (i.e., the fixation disparity) was measured for each observer and compensated for by offsetting the center disk. This measure improved the alignment but a perfect alignment was still not guaranteed due to constant vergence eye movements. Thresholds were measured under the transient condition for three background conditions of center-disk only, dichoptic annulus, and monoptic annulus (a 19' monoptic disk). The results (Fig. 2) show that the dichoptic annulus did not lower the threshold, but rather elevated it, consistent with previous reports (e.g., Westheimer, 1967). However, when observers (and one author, DL) were asked what they saw under the dichoptic annulus condition, all reported that instead of seeing a full circular disk, they always perceived a bright ring with a dark inner center. The inner center was perceived to be even darker than the outside screen. Thus, it appears that the brightness of the center disk and target was suppressed by the dichoptically added annulus. This suppression made the target harder to detect and elevated the threshold.

To examine this brightness suppression under sustained conditions, a constant annulus was presented to the left eye and a center disk to the right eye. The dimensions of both objects were the same as in the experiment described above. The position of the annulus was fixed on the center of the screen, but the position of the center disk could be adjusted by a hand-controlled trackball which allowed observers to move the disk into the center of the annulus and obtain proper ocular alignment. Observers were asked to "see aloud", i.e., orally report their perception while fixating on the stimuli. A typical process of binocular rivalry was reported. As soon as it entered the annulus, the center disk disappeared and only the annulus could be seen. Then the annulus disappeared and the center disk reappeared. This rivalry process occurred continuously throughout the viewing period. In general, the annulus always suppressed the center disk first, lasting for about 8–10 sec on the average, which explains why only a ring was perceived under transient conditions. The duration that the center disk was perceived was about 2–4 sec. The transition between the annulus perception and the center disk perception (i.e., both objects were perceived simultaneously as a full circle) was the shortest, usually less than half a second.

We also examined the possibility that binocular rivalry influenced the perception of the stimulus configuration in Experiment 1. Binocular rivalry reported for that con-

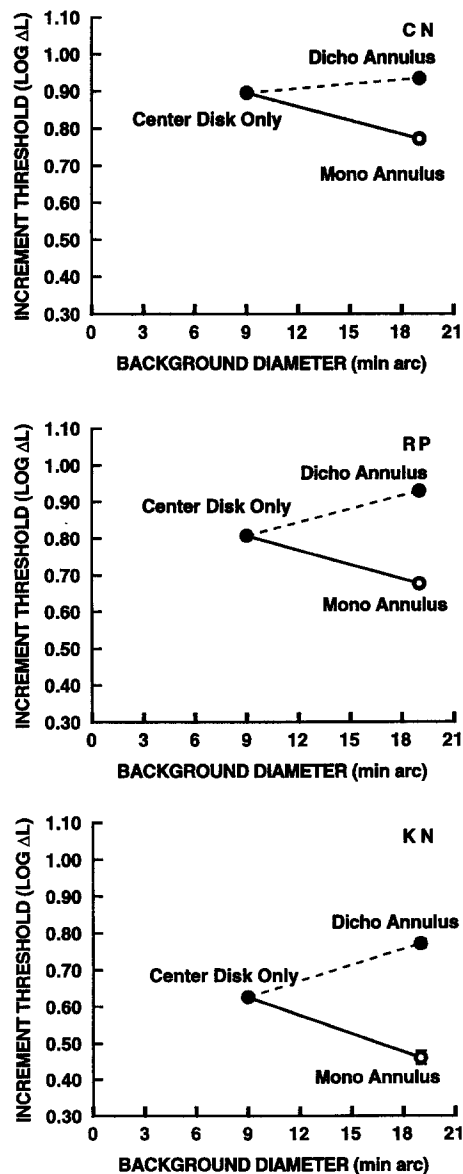


FIGURE 2. Effects of dichoptic and monoptic annuli as compared with the effect of only the peak-diameter center disk (no annulus). Data were collected under transient conditions.

figuration was actually very weak and brief (1 or 2 sec), and did not occur until the target-on-background perception had lasted for about 10–15 sec. Thus, the results of Experiment 1 were relatively immune to the effects of binocular rivalry.

Regarding the threshold elevation in dichoptic annulus experiments, Sturr and Teller (1973) conjectured that the onset of the dichoptic annulus could shift the ocular dominance to the non-test eye so as to elevate the threshold in the test eye. This conjecture is consistent with the first stage (annulus dominant) of the above binocular rivalry process. However, under constant stimulus conditions, observers could actually detect the target when the disk was dominant, which may explain the equal or only slightly elevated thresholds reported in some experiments (e.g., Westheimer, 1967). Since the transition stage (both objects are perceived) is very brief and unstable (one object fading in and the other fading

out), dichoptically transferred information (if any) could hardly be used to lower the threshold. In general, these dichoptic annulus experiments appear to be dominated by binocular rivalry, and provide little information about the neural locus of the Westheimer function.

EXPERIMENT 3: DICHOPTIC MEASUREMENTS WITH THE TARGET ON DICHOPTICALLY ALIGNED DISKS

This experiment attempted to demonstrate interocular transfer of sensitization following the same logic of dichoptic annulus experiments while avoiding the effects of binocular rivalry. The main difference between this and previous dichoptic annulus experiments was that the background disk was presented to each eye. Specifically, one peak-diameter disk (9' in diameter) with the spot target superimposed was presented to the right eye, and a second disk whose diameter was equal to either the peak diameter (9') or 19' was presented to the left eye. When two disks were aligned using the trackball, binocular rivalry was rarely perceived. The perception was a single disk with a spot target superimposed, either with (19' disk) or without (9' disk) a dimmer annulus. Thus, any threshold reduction as the size of the disk seen by the left eye was increased from 9 to 19' could be interpreted as the interocularly transferred sensitization effect.

During the measurements, the target and disk seen by the right eye were constantly presented on the center of the screen. The disk seen by the left eye was also constantly presented, but its position could be adjusted with the trackball. Increment thresholds for the spot target were measured using the method of adjustment. Observers used their left hand pressing the "1" or "2" key on the computer keyboard to increase or decrease the target luminance, and used their right hand to control the trackball. They were asked to make their judgments as soon as, and only when, the two disks were aligned. Several sessions of practice were used before data collection.

Figure 3 presents the mean threshold of each observer over 40–50 trials. We first measured the same three observers as in previous experiments. Two observers' results (CN and RP) showed a significant threshold decrease with enlarged disk diameter, suggesting interocular transfer of the spatial sensitization effect. However, such a threshold decrease is not evident in observer KN's results, which are essentially a flat function. This observer reported some difficulty in aligning the objects and detecting the target at the same time, but she claimed that the situation had been improved greatly after several sessions of practice. Thus, it is not clear why her performance differs from those of other observers. We decided to run one more observer (TN) to clarify the results. As seen in Fig. 3, clear sensitization is also shown.

The continuous trackball control of object alignment in this experiment effectively eliminated the effects of ocular misalignment seen in our earlier dichoptic measurements and in other dichoptic experiments (e.g.,

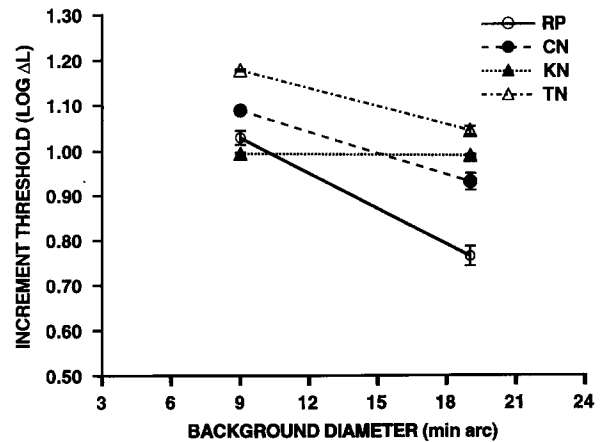


FIGURE 3. Sensitization effects of a dichoptically added annular region with the effects of binocular rivalry minimized.

Sturr & Teller, 1973), and the constantly presented stimuli are comparable to the steady stimuli usually used by other researchers (e.g., Westheimer, 1967). Thus, this test provides evidence that the sensitization effect can be interocularly transferred under sustained or steady conditions, at least for some observers. This conclusion is consistent with that of Experiment 1, and suggests that the Westheimer function is, predominantly, cortically determined. Note that despite our efforts to minimize rivalry and vergence fluctuations, one of our four observers did not show transfer, indicating the fragility of these dichoptic effects.

EXPERIMENT 4: THE WESTHEIMER FUNCTION IN HUMANS WITH NATURALLY ACQUIRED AMBLYOPIA

In this experiment the Westheimer function was measured in two amblyopes. Amblyopia is basically a developmental anomaly of cortical mechanisms (e.g., Levi, 1990), and there is no strong evidence of any primary retinal abnormality in humans and primates with amblyopia (e.g., Hess & Baker, 1984; Movshon & Van Sluyters, 1981; Hendrickson *et al.*, 1987; Movshon & Kiorpes, 1993). Thus amblyopia could serve as an ideal means to test the potential modulation of the visual cortex on the Westheimer function.

As in Experiment 1, experiments were conducted under both sustained and transient conditions. Both the preferred and amblyopic eyes were measured. Results are presented in Fig. 4. The overall threshold level of the amblyopic eyes' functions is elevated, showing the well known and significant loss of contrast sensitivity in amblyopic eyes (e.g., Hess & Howell, 1977; Levi & Harwerth, 1977). However, desensitization and sensitization processes are differentially affected by the defect. Amblyopic functions show a much slower and wider sensitization process as compared with the non-amblyopic functions. The sensitization branch ends at a background diameter of about 45' for AJ and at least 65' for RH, as compared with about 15' in both observers' non-

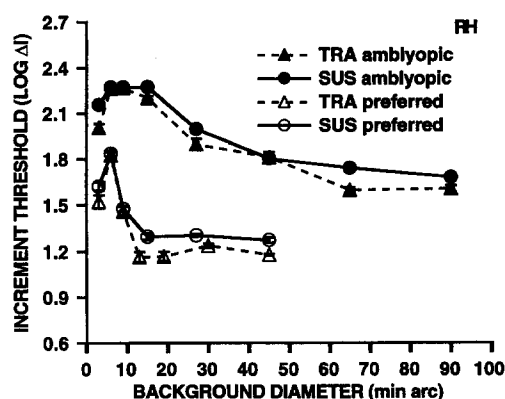
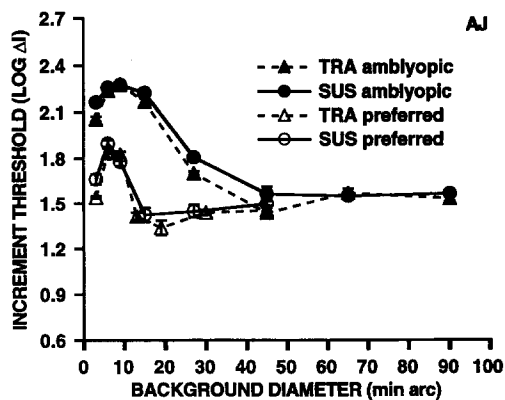


FIGURE 4. Westheimer functions measured in amblyopic and preferred eyes under sustained and transient conditions (SUS, sustained; TRA, transient).

amblyopic data. Meanwhile, the desensitization process of amblyopic eyes is less affected. The peak shift of the amblyopic functions suggests only moderately enlarged desensitization branches, about 9–13', in contrast to 6' in non-amblyopic functions.

From the point of view of psychophysical perceptive fields, these data suggest that amblyopic perceptive fields in the central visual field have moderately enlarged summation centers, and a greatly enlarged inhibitory surrounds. These foveal amblyopic functions are comparable with functions measured at the periphery of normal adult observers (Yu & Essock, 1996b). All show considerably extended sensitization branches and only moderately enlarged desensitization branches. This similarity suggests that foveal mechanisms with finer receptive fields may have been selectively abolished in amblyopic eyes.

As suggested in Experiment 1, these curves virtually show no difference between sustained and transient functions, for either preferred or amblyopic eyes, suggesting that both functions are similarly affected by amblyopia and could be processed by similar cortical mechanisms.

GENERAL DISCUSSION

We measured the Westheimer function in normal observers under dichoptic conditions, and in observers with amblyopia, in order to assess the locus of the effect. Our main results show interocular transfer and abnormal amblyopic modulation of the Westheimer function. These results, combined with steep spatial scaling of spatial sensitization (Yu & Essock, 1996b), form three convergent lines of evidence, suggesting that the visual cortex makes a strong contribution to the Westheimer function in human cone vision.

Interocular transfer of the Westheimer effect

Our dichoptic results provide some insight into the mixed results of earlier dichoptic studies. Experiment 2 suggests the strong effect of binocular rivalry in dichoptic annulus experiments (e.g., Westheimer, 1967), and Experiment 3 suggests significant interocular transfer of spatial sensitization in three of four observers when binocular rivalry is minimized, so that previous evidence supporting the retinal hypothesis of the Westheimer function from dichoptic annulus experiments has to be reconsidered. The striking similarity between monocular and dichoptic Westheimer functions when rivalry and fixation disparity are minimized is not consistent with a retinal basis for the Westheimer function.

Experiment 1 also offers clear evidence of interocular transfer of the entire Westheimer function when the target and background are presented to different eyes, which was also reported by Markoff and Sturr (1971), but not by Johnson and Enoch (1976). The overall paradigm under sustained conditions in Experiment 1 is similar to that of Johnson and Enoch's, but the latter showed flat dichoptic functions. Although the reason for this difference is unclear, one aspect worth mentioning is that Johnson and Enoch reported lower dichoptic thresholds, which is not only inconsistent with our results, but also contradictory to general findings that stimuli presented to one eye tend to raise thresholds in the other eye (Fox & Check, 1966; Legge, 1979; Levi & Harwerth, 1982). Lower dichoptic thresholds in Johnson and Enoch's experiments suggest that their dichoptically presented background did not function properly, which could have been caused by ocular misalignment, or by other reasons. As in Markoff and Sturr's (1973) study, our dichoptic curves share similar peaks to those of the monoptic curves. This coincidence suggests that very likely the same mechanism underlies both the dichoptic and monoptic functions. The substrate of this mechanism can be as early as in area V1, where many cells are driven binocularly, as opposed to the retina or the LGN, where neurons from one eye do not or rarely have direct connections to the other eye. These curves also suggest that both the sensitization and desensitization branches of the Westheimer function have a cortical substrate.

An abnormal Westheimer effect in amblyopia

Our amblyopia testing results are comparable with results reported by Lawwill *et al.* (1973). Although they

used the abnormal amblyopic function to infer a possibly impaired retinal structure in amblyopic eyes, their inference is problematic since the processing locus of the Westheimer function itself is still open to question. Furthermore, recently many lines of evidence have suggested that the retinal structures of amblyopic eyes of humans and primates are basically intact and the defects are mainly cortical. Hendrickson *et al.* (1987) and Movshon *et al.* (1987) reported that the retina and all other eye tissues were normal in monocularly deprived animals, and cells in the parvocellular layer of the LGN had normal physiological properties. Blakemore and Vital-Durand (1986) and Levitt *et al.* (1989) reported that the spatial and temporal properties of LGN neurons in long-term deprived monkeys were essentially normal. Hess and Baker (1984) also reported either no or only minimal pattern ERG abnormalities in deep amblyopes, which could not be linked with their psychophysical anomalies. Meanwhile, the most profound and consistent effects of the amblyopic process are found in the striate cortex. Both surgical strabismus and prism rearing lead to a massive loss (around 80% or more) of binocular neurons (Baker *et al.*, 1974; Crawford & von Noorden, 1979, 1980). Neurons driven through the amblyopic eye in cats show reduced contrast sensitivity, particularly at high spatial frequencies (Eggers & Blakemore, 1978). Similar results were also obtained in monkeys reared with chronic atropinization (Kiorpes *et al.*, 1987; Hendrickson *et al.*, 1987; Movshon *et al.*, 1987) and experimental strabismus (Movshon & Kiorpes, 1993) along with shrinkage of ocular dominance columns of the treated eye.

These studies provide strong support for the notion that the primary effects of amblyopia are cortical. Thus, in our opinion, it is more appropriate to test the Westheimer function with amblyopia rather than to test amblyopia with the Westheimer function. However, the amblyopic results, as well as the dichoptic results, only suggest the effects of the visual cortex on the Westheimer function, they do not exclude the role of any pre-cortical mechanisms. The findings that the sensitization effect is diminished but not abolished in stabilized vision (Tulunay-Keesey & Vassilev, 1974; Hayhoe & Smith, 1989) and is shown in bleaching stimuli (Hayhoe, 1979a) provide evidence for retinal components of the Westheimer function. Single-unit recording results similar to the Westheimer function were also found in LGN cells (Essock *et al.*, 1985). However, neither of these results is consistent with a purely retinal theory of the Westheimer function.

One important reason for assuming the retinal contribution of the Westheimer function has been that concentric circular receptive fields suggested by this function resemble circular receptive fields of retinal cells. This agreement, however, could occur simply because a spot target and a circular background were used. When they were replaced by a line target and a rectangular background and the width of the background was varied, a similar function was produced which could be taken to

suggest elongated perceptive fields (Essock & Krebs, 1992; Yu & Essock, 1996a), like elongated receptive fields found in cortical area V1. The functions measured with either circular or rectangular stimuli not only share the same desensitization and sensitization ranges, but also have identical E_2 values when measured across the visual field (Yu & Essock, 1996b), as well as similar dichoptic properties and amblyopic modulations (Yu & Levi, 1997). Thus it is very likely that these two functions are based on the same neural mechanism and that the perceptive fields implied in the Westheimer function are not necessarily circular.

Size-tuned cortical filters and the Westheimer effect

The Westheimer function or the cortical perceptive fields it represents may be understood on the basis of size-tuned cortical spatial filters (e.g. Wilson & Gelb, 1984). These spatial filters, usually modeled after simple cell receptive fields, have an elongated excitatory center and inhibitory flanks. An enlarged background, either circular or rectangular, can first summate central excitation and then elicit inhibition of spatial filters, therefore producing a Westheimer effect. The involvement of cortical spatial filters in the sensitization effects was first suggested by Lennie and Macleod (1973) and Latch and Lennie (1977) on the basis of rod-cone interactions they observed in sensitization. This suggestion is not only supported by our data, but also further detailed by Makous (1997), who nicely interpreted the Westheimer function in the Fourier domain. Moreover, Makous and Bex (personal communication) found that, when masked by a radial grating, the threshold for a test flash was highest when the spatial frequency of the mask was 8 cpd, and was reduced as the frequency was either higher or lower. The masking effects were independent of the mask phase, thus clearly indicating cortical processing. In general, the cortical spatial filter hypothesis is able to account for most evidence which fits both the cortical and the retinal theories. It also has the advantage that it can accommodate the steep spatial scaling of spatial sensitization (Yu & Essock, 1996b), interocular transfer and abnormal amblyopic modulation of the Westheimer function (this paper), and Makous and Bex's masking results. For instance, the enlarged peripheral Westheimer function could reflect the scale change of peripheral spatial filters (Levi & Waugh, 1994), and the abnormal modulation of amblyopia on the Westheimer function could be explained by the loss of spatial filters tuned to fine spatial frequencies in amblyopic eyes (Levi *et al.*, 1994). None of these is easily explained by the retinal theory.

Alternative explanations

Despite a great deal of experimentation and modeling, the locus of the Westheimer effect has proven quite intransigent (see Teller, 1980 for an excellent discussion of the locus problem). When measured with spots and annuli, the typical U-shaped curve was frequently (but not always) thought, by analogy to the center-surround properties of concentric retinal ganglion cell receptive

fields, to represent the responses of retinal ganglion cells. The experiments and modeling discussed above suggest that a simple retinal based model is unlikely. The main contribution of the present paper is to show that: (1) when the substantial and significant effects of rivalry and fixation disparity are carefully controlled, the Westheimer effect shows interocular transfer; and (2) that the Westheimer effect is abnormal in observers with amblyopia. In combination, we argue below that these results provide strong qualitative evidence for a cortical locus.

Interocular transfer provides clear evidence that a cortical locus is sufficient, but does it imply that a cortical locus is necessary? For example, one could argue that sensitization can occur both retinally and cortically. In this view, in the monoptic case, sensitization could be retinal, reducing threshold, and in the dichoptic case some central process could take place which also reduces threshold. We believe that this is unlikely. The striking similarity between the monocular and dichoptic effects (see Fig. 1) suggests that the same processes are active in both. In addition, thresholds are always higher in the dichoptic case; however, a simple retinal theory (ignoring the "and nothing mucks it up" principle; Teller, 1980) would predict that the test spot would be detected at a lower contrast by the retinal mechanisms, which cannot be affected by the annulus in the other eye.

Teller (1980) argues that for the retinal model to work, the specific retinal cell must be the most sensitive to the test-spot (i.e., the cell represents the "weakest link"). The extant evidence suggests that the amblyopic process does not disturb the retina in any important way. Rather, amblyopia exercises its effects at the cortex. Thus, a simple retinal theory would not predict any alteration in the Westheimer function in the amblyopic visual system. On the other hand, our observations of interocular transfer and amblyopic deficits are readily understood on the basis of cortical spatial filters.

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