Interocular transfer

An assessment of binocularity in strabismus[1]

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The interocular transfer of the motion aftereffect (MAE) was used to probe for the existence of binocularity in subjects with strabismus. The interocular transfer was measured with coarse and fine gratings subtending 2° and 8° of visual angle. Strabismic subjects were categorized by the extent of their binocular vision, particularly with respect to extrafoveal fusion and retinal correspondence. Subjects classified as having the monofixation syndrome consistently showed a substantial, though less than normal, amount of transfer with the larger 8° gratings. This is consistent with the peripheral binocular cooperation usually found in these subjects, and establishes interocular transfer of the MAE as a suitable test for binocularity in strabismus. The test is especially suitable in patients with suppression in which an existing binocularity may be masked by suppression on clinical testing. The tests were found to be applicable in children as young as eight years. MAE tansfer for large coarse gratings is believed to imply the existence of an early cortical binocularity, which provides the potential for sufficient binocular cooperation to permit stable ocular alignment.

Index term: Strabismus

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Stimulus specificity for binocular cortical neurons

Animal experiments indicate that most visual cortical neurons, at least those coming from the fovea, are binocular. That is, they can be excited by either eye but they respond optimally when both eyes are stimulated simultaneously.[1–3] Each neuron is also highly selective as to visual stimulus location and parameters, such as contour orientation, spatial detail, and direction of motion. If a stimulus

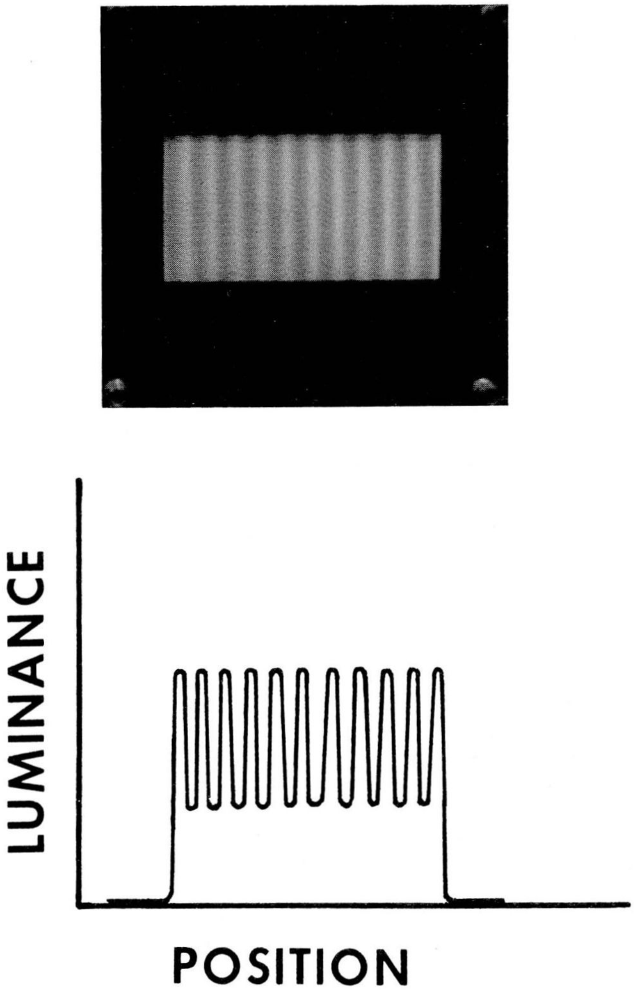


Fig. 1. The spatial luminance profile of a sine wave grating is shown beneath the photograph of the CRT display.

presented to only one eye results in a strong response of a given cortical neuron, then this same stimulus presented at the corresponding retinal location of the contralateral eye will also result in a strong response.[4] A given neuron usually shows an ocular dominance, but responds best when stimulation is simultaneously presented in both eyes and at corresponding retinal locations.

Visual stimulus specificity is usually described by receptive field size and location, spatial detail, contour orientation, temporal modulation, and direction of motion. *Receptive field size and location* is the region of the visual field where a stimulus will elicit a response. *Spatial detail* refers to the nature of the visual stimulus, which varies from a single edge, to a bar, to a periodic striped pattern or grating whose luminance is modulated sinusoidally. The *spatial frequency* of a periodic pattern refers to the number of cycles (one light and one dark bar) per degree of visual angle. *Contour orientation* refers to the angular orientation of the edge, bar, or grating that constitutes the stimulus, i.e., vertical, horizontal, or oblique. *Temporal modulation* indicates when the stimulus is on; it may be presented continuously, for a short time interval, or repetitively in a sinusoidal or on/off manner. *Direction of motion* refers to the direction in which the stimulus is moving within the receptive field, e.g., from nasal to temporal or temporal to nasal.

Sine wave gratings (*Fig. 1*) have been used extensively as visual stimuli in research because of the fundamental nature of such a stimulus both in terms of being able to construct complex patterns from gratings and because cortical neuron selectivity appears to be well tuned to a sine wave grating.[5] Gratings with precise contrast, orientation, spatial frequency (spatial periodicity), and speed can be generated and controlled electronically on a CRT display (oscilloscope). We have used gratings generated in this manner for most of our experiments. *Figure 1* shows that these gratings appear simply as a series of bars moving across the screen.

Motion aftereffect and interocular transfer

Motion aftereffect (MAE) can be induced by visual adaptation to a moving grating (viewing the moving grating for a period of time). When the motion is stopped, the stationary grating will appear to drift slowly backwards. This apparent backward motion, which decays slowly in time, is the MAE. The duration of the MAE, typically about 30 seconds, is a measure of its strength or magnitude. In subjects with normal binocular vision, the MAE transfers interocularly. That is, if the moving stimulus is presented to only one eye while the other eye is covered, and then the stationary grating is presented only to the contralateral (previously covered) eye, the aftereffect can be seen with this contralateral eye alone. This normal result is explained on the basis that adaptation to the moving grating occurs at binocular neurons in the brain, which can be excited by either eye, and thus the effect of the adaptation (as manifested by the MAE) can be seen through either eye. This therefore constitutes a test for the presence of binocular neurons. The interocular transfer of the MAE has been used in our studies to probe for the existence of binocularity in normal and strabismic subjects.

Interocular transfer and suppression

Previous studies suggest that the binocularity examined by the interocular transfer of the MAE is located at a low level of visual processing. Evidence for this comes from experiments that studied the effect of binocular retinal rivalry suppression on the aftereffect.[6–8] Retinal rivalry occurs when each eye views a different target. Instead of the two targets being seen simultaneously or superimposed, only one, the other, or parts of both targets are seen with no superimposition occurring. This is a form of suppression and occurs in normal individuals. *Figure 2* shows a schematic diagram of the adaptation paradigm for the effect of rivalry on the MAE. The left eye is being adapted by a rightward-moving grating and simultaneously the right eye views a stationary but horizontally oriented grating. This presentation causes retinal rivalry and, as long as the visual angle of the display is less than 2° or 3°, the subject alternates between perceiving the rightward-moving grating and the stationary grating. Retinal rivalry suppression does not allow one to perceive a superposition or a mixture of the two competing (different) gratings, but rather one of the gratings is alternately suppressed. Thus during some of the adapting period, the subject does not see the moving grating because of retinal rivalry suppression. The question that these experiments answered is: Does the rivalry suppression reduce the adaptation to the moving grating? Surprisingly, the answer is clearly no. The experiments showed that the sensorial suppression did not reduce the adaptation caused by the moving grating as evidenced by no reduction in either the monocular MAE or in its interocular transfer. Because the adapting stimulus (moving grating) was found to be effective even during its suppression (by the stationary grating), these authors concluded that the neurons believed to mediate the aftereffect were located at a cortical level lower than those mediating retinal rivalry suppression.

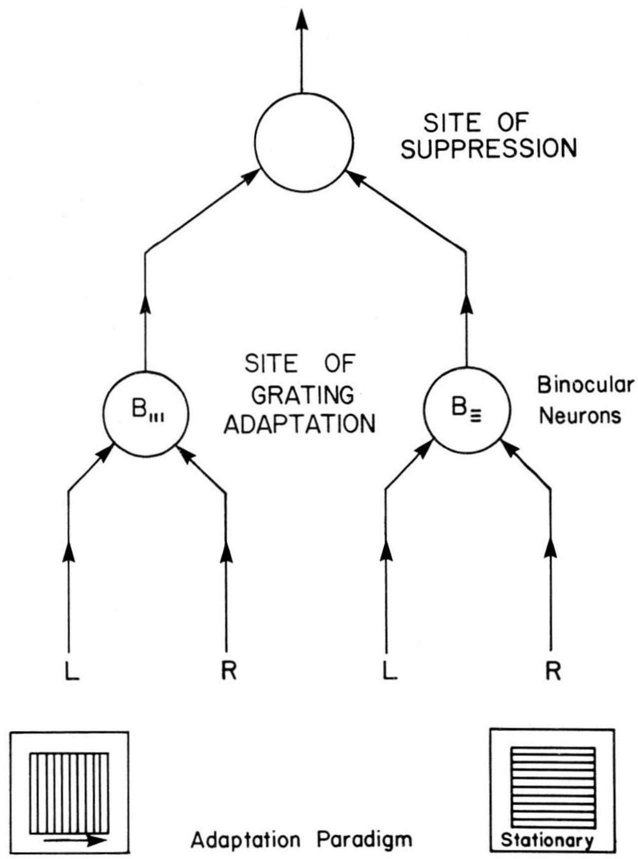


Fig. 2. Schematic diagram of the adaptation paradigm to study the effect of retinal rivalry on the MAE. A moving vertical grating is presented to the left eye while a rivalrous stationary horizontal grating is presented to the right eye. The two stimuli affect different binocular neurons.

Interocular transfer in strabismus

The foregoing suggests that it would be useful to study the interocular transfer of the MAE in strabismic subjects who suppress the information coming from one eye to various degrees. If this suppression also occurs at a higher level than the neurons mediating the MAE, then one could probe with interocular transfer measurements for the existence of functional binocular neurons before the point of suppression in strabismus. In strabismus, the eyes are misaligned and, therefore, noncorresponding retinal regions receive the same stimuli that results in diplopia in normal individuals. In strabismic children, the diplopia is avoided either by suppressing the image from one eye, or by suppressing and adapting an abnormal relationship between the two eyes such that an abnormal correspondence is established. A clinical assessment of binocularity in strabismus is based primarily on perceptual and subjective responses to test patterns that are designed so that suppression can be accurately mapped. *Thus,* *clinical tests determine the extent of suppression, whereas interocular transfer determines the status of early cortical binocularity. This distinction has important implications for the restoration of binocular vision because binocularity could never be restored even by the elimination of suppression if at least some of the cortical binocular connections are not intact.* Because each cortical neuron has its own receptive field and responds best to a specific stimulus, one might expect to find binocularity for certain groups of neurons, and at the same time a lack of binocularity in others. The interocular transfer of the MAE allows a probing of different cortical neuron groups by using gratings varying in size, spatial frequency, orientation, and retinal location. Our previous studies compare such MAE transfer measurements with clinical findings in subjects with strabismus.[9,10]

Patients and methods

Clinical assessment of binocularity in strabismus

The clinical examination of the subjects participating in our studies categorized each subject's binocular vision, particularly with respect to foveal fusion, peripheral fusion, and retinal correspondence. Clinical data for each strabismic subject include an estimate of the time of onset of the strabismus, previous surgery, angle of deviation, amblyopia, and a mapping of suppression. Subjects were classified in the following groups: normal (N), monofixation syndrome (M), alternating strabismus (ALT), and anomalous retinal correspondence (ARC) with a large deviation. The subjects in the three strabismic groups differ primarily in the extent of binocular cooperation, which is attributable to the extrafoveal retinal regions, as none of the strabismic subjects had bifoveal fusion.

Subjects were classified as having the *monofixation syndrome* on the basis of a suppression scotoma of the central 3° fixation area in binocular vision in one eye, peripheral fusion including the presence of coarse stereopsis at near, and fusional vergence amplitudes, which also indicates peripheral fusion. The angle of deviation in these subjects is generally less than 8 prism diopters.

Subjects classified as having *alternating strabismus*, with or without amblyopia, had total retinal suppression of one eye, i.e., no stereopsis, no peripheral fusion, and no simultaneous perception of visual information coming from each eye. If a subject showed the slightest indication of peripheral fusion in even one of the tests, they were excluded from this group.

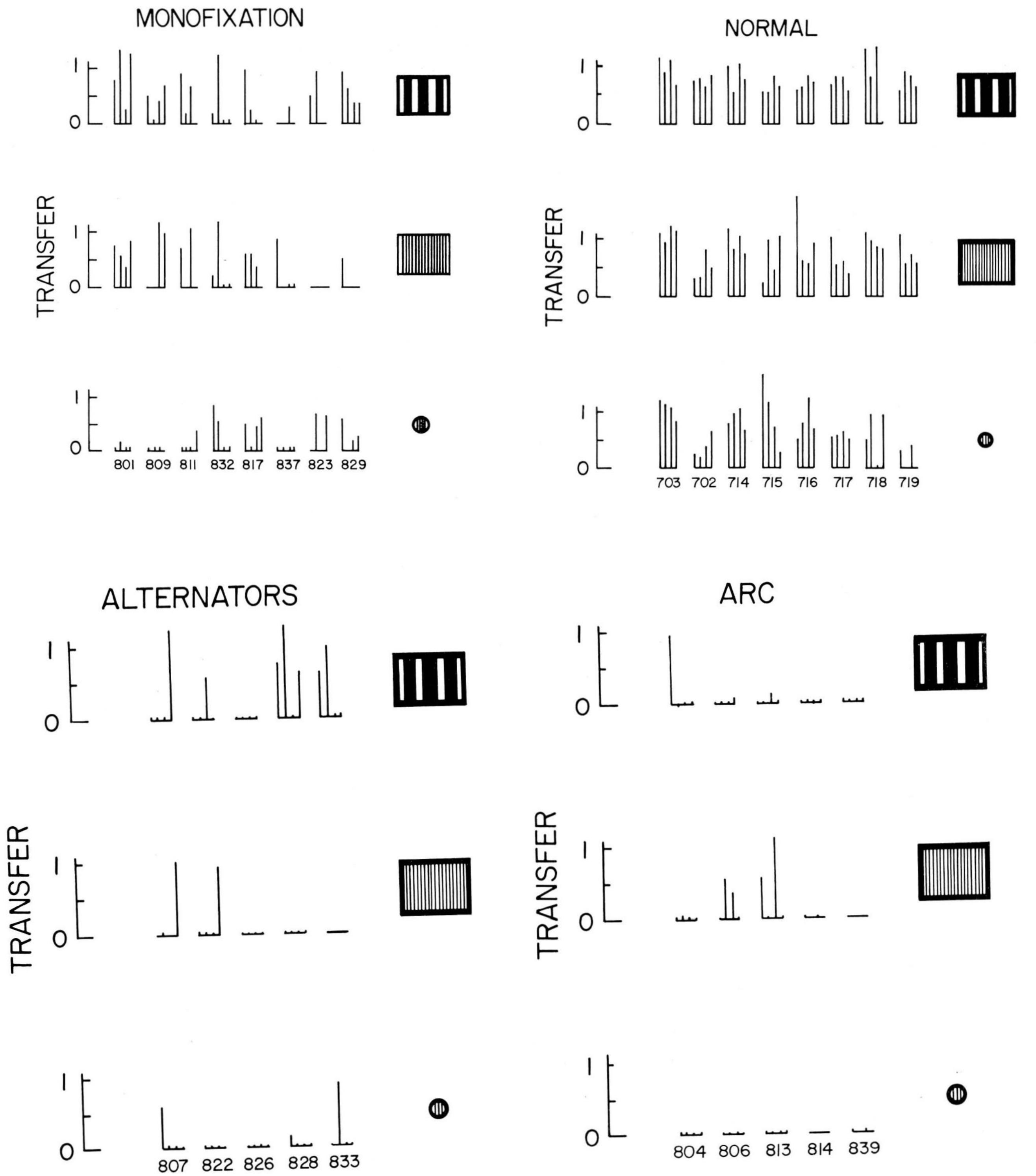
In *anomalous retinal correspondence* there is a simultaneous perception of retinal information from the peripheral retinal region of the deviating eye and an anatomically different retinal region of the fixing eye. All of these subjects had a history of esotropia in childhood, but the age of onset was indeterminate. None had strabismus surgery and all remained esotropic with large angles of deviation over an extended period of time.

A total of 11 children, 10 of whom had strabismus, between the ages of eight and 15 were seen as part of this study, but only 6 of the 11 could perform sufficiently well on the clinical testing to permit unambiguous clinical sensory classification, and thus be included in the data. However, all 11 gave adequate and consistent responses to MAE transfer testing.

Measurement of interocular transfer

Instrumentation. Sinusoidal gratings having a spatial frequency of either 0.5 or 3 c/degree were presented on two oscilloscopes, which were placed on a table in a haploscopic arrangement. The gratings could be oriented either horizontally or vertically. The right eye had a free view of one oscilloscope placed 1 m ahead. At this distance, the gratings subtended an angle of 8°; 2° gratings were obtained by placing a mask over the oscilloscope face. A small rectangular mirror subtending 9° was positioned close to the subject's left eye and was adjusted with the subject's right eye covered so that the second oscilloscope (placed off to the left) appeared superimposed on the screen of the first oscilloscope located straight ahead. A small blind to the left of the subject's head prevented a direct peripheral view of the left oscilloscope. Typically the subject was aware only of the oscilloscope located straight ahead. The gratings were either stationary or moved at a speed that resulted in a temporal frequency of 5 c/sec at any point on the screen.

Procedure. The experimental paradigm consisted of two types of trials: monocular and interocular. In the monocular trial, the moving grating was presented to one eye only for a 1-minute adaptation, while a blank field with the same mean luminance was presented to the contralateral eye. This was followed by a 35-second stationary test grating presented to the adapted eye,



Figs. 3–6. Four motion aftereffect interocular transfer measurements are shown for each subject (indicated by number) and for each grating illustrated. The order of the four MAE transfers shown for each condition are: right eye to left eye transfer with horizontally oriented grating, right to left with vertical grating, left to right with horizontal grating, left to right with vertical grating.

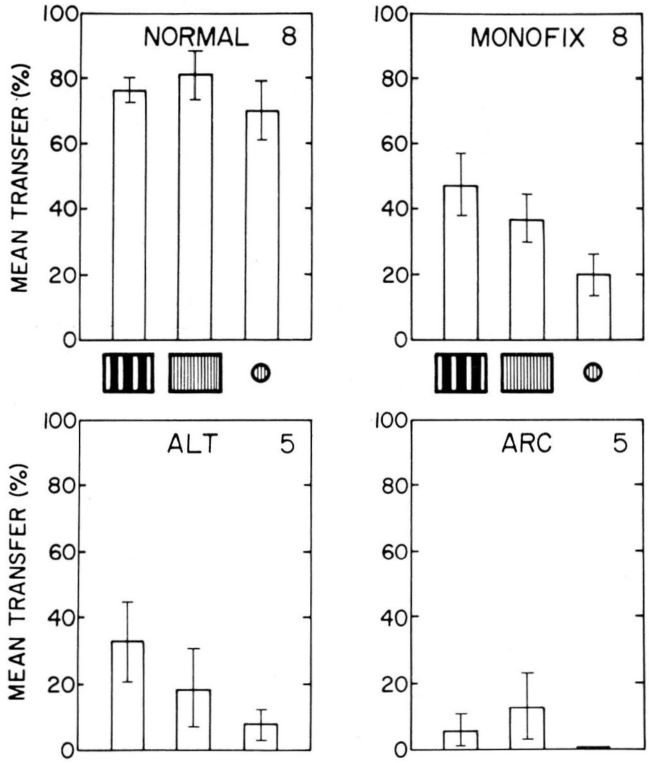


Fig. 7. Summary of individual data. Each bar is the mean transfer of the four trials for all subjects in the group. The error bars show the standard error of the mean.

while the blank field was continued in the contralateral eye. In the interocular trial, the adaptation was the same as in the monocular trial, but the stationary test grating was presented to the contralateral eye while a blank field was presented to the adapted eye. Subjects were instructed to maintain fixation on a small X in a circle centered on the oscilloscope screens during the entire session. Subjects with strabismus did not use prisms; they were instructed to fixate either the stationary or the moving grating. Thus transfer was measured between foveally-centered areas, or between anatomically corresponding retinal regions. In the presence of dense amblyopia, occlusion of the normally seeing eye was frequently used to ensure proper fixation with the amblyopic eye. No subject had eccentric fixation, so that grating fixation was central in all subjects. A typical duration of the MAE for a monocular trial was 20 to 25 seconds.

Calculation of the interocular transfer. For each subject, the motion aftereffect was measured for both horizontally and vertically oriented gratings. For each grating orientation, there were two monocular trials, right-to-right (RR) and left-to-left (LL), and two interocular trials, left-to-right (LR) and right-to-left (RL). All subjects had nonzero MAEs for all monocular trials. We found no significant difference at $P < 0.05$ using Student's t test between the monocular MAE for horizontal versus vertical gratings or for right eye versus left eye. Therefore, we averaged the four monocular MAE durations to obtain the mean monocular MAE duration, M:

M = mean MAE duration of the four monocular trials:

RR and LL horizontal, RR and LL vertical.

The interocular transfer is obtained from an interocular trial by forming the ratio:

Transfer = interocular MAE duration/M

There are four interocular transfers for each subject: RL horizontal, RL vertical, LR horizontal, and LR vertical.

Results

Interocular transfer by clinical categories

We present here a summary of our interocular transfer measurements for 26 subjects, some of which have been published previously.[9,10]

Figures 3–6 present the four interocular transfer measurements for each subject with a given grating. The grating used for the transfer measurements is schematically illustrated on the right (0.5 c/degree subtending 8°, 3 c/degree subtending 8°, 3 c/degree subtending 2°); the subjects are grouped together by clinical category.

The 8 normal subjects all showed substantial and similar transfer for all three gratings.

The 8 subjects classified as monofixators typically show a moderate, but less than normal, amount of transfer with the large coarse grating. There is less transfer with the large fine grating, and much less transfer for the 2° fine grating. This pattern was fairly consistent in these subjects.

The 5 subjects classified as alternators showed a considerable variation across subjects. Three of the subjects (nos. 807, 822, 825) show either no transfer or transfer for one or two conditions only, whereas 2 other subjects (nos. 828, 833) show a transfer for the coarse grating.

The 5 subjects classified in the ARC group consistently show either no transfer or a negligible amount. Because of the development of an abnormal retinal correspondence in these subjects, we thought that we might find transfer between the anomalously corresponding regions rather than the anatomically corresponding regions. In 2 subjects (nos. 813, 814) with ARC, we adapted the anomalously corresponding peripheral retinal region of the deviated eye and then tested for transfer in the central region of the normally fixating eye. The amount of interocular transfer did not increase. We thus conclude that these subjects do not exhibit interocular transfer between either anatomically or anomalously corresponding retinal regions.

Figure 7 is a summary of the individual data. Each bar is the mean transfer of the four trials for all subjects in the group. The error bars show the standard error of the mean.

Normal subjects showed 70% to 80% transfer with all three gratings. Subjects with the monofixation syndrome showed a substantial amount of transfer with the 8° coarse and fine gratings, but not with the 2° grating. In the alternator group, the group mean transfer with the 8° coarse grating is due only to the good transfer shown by two subjects in this group (*Fig. 5*); there is not a typical response for subjects in this group. And finally, subjects in the ARC group showed only minimal transfer to all gratings.

These results show that overall the amount of interocular transfer of the MAE (for the coarse grating) does correlate with the clinical assessment of binocularity. However, in individual cases, especially in the alternator category, we found evidence of cortical binocularity from the transfer measurements, whereas binocularity was not indicated from the clinical examination.

Discussion and conclusions

For all strabismic subjects, regardless of classification, there is virtually no interocular transfer with the 2° grating. That is, the 2° grating cannot be used to distinguish between strabismic subjects. This result might have been predicted from the fact that none of the strabismic subjects had bifoveal sensory fusion. ***What distinguishes the strabismic subjects in the three groups is the extent of binocular cooperation between the extrafoveal retinal regions of both eyes.*** For example, those subjects with monofixation do have peripheral binocular vision (including some stereovision), and they do show a substantial amount of transfer with the large "peripheral" 8° gratings. However, such transfer is not found in subjects with a large deviation who have developed an anomalous peripheral binocular cooperation between the eyes (subjects in the ARC group).

It is the binocular cooperation in the extrafoveal retinal regions that correlates with MAE transfer when low spatial frequency gratings subtending 8° are used. We assume that MAE transfer implies a cortical binocularity at a low level of visual processing, i.e., one lower than those mediating sensory suppression or stereopsis. Stereopsis is generally thought to be associated with a higher level of binocularity. Wolfe and Held[11–13] found a purely binocular process, i.e., one that requires the simultaneous stimulation of each eye, which they believe is responsible for stereopsis. Such a binocularity is not tested with the interocular transfer of the MAE because only one eye is stimulated at a time. This is probably the reason why neither the previous investigators[14] nor we have found any correlation between interocular transfer and stereoacuity. MAE transfer and stereopsis appear to deal with different cell populations, and therefore, MAE transfer could not predict stereoacuity.

At first it appears puzzling that some subjects with alternating strabismus (total suppression from one eye) were found to show any transfer. However, as described previously, retinal rivalry suppression did not prevent adaptation of binocular cells through the suppressed eye, and thus it might be expected that suppression in strabismus also might not interfere with measuring MAE transfer. If MAE transfer is found in these subjects, it does imply the existence of an early binocularity at a cortical level lower than that mediating the suppression of clinical binocularity.

From the above we conclude that interocular transfer of the MAE can be used as a test for the presence of binocularity in patients who do not show clinical evidence of binocularity. In order to facilitate such testing, we have developed a simpler way to measure the interocular transfer of the MAE. This method makes use of a rotating sectored disk, rather than a CRT grating display. It is more suitable for routine clinical testing because it is both simpler to administer and easier for subjects to respond to.

The above results also have some implications for ocular alignment. Normal subjects maintain precise ocular alignment and show good interocular transfer for all of the gratings used. Subjects with monofixation also maintain ocular alignment, however, at their small constant angle of deviation. Their interocular transfer for the fine 2° gratings is substantially reduced from normal, and for the coarse 8° gratings it is about 60% of normal. Since these subjects had small angles of deviation, the 8 degrees of visual angle subtended by the gratings precludes being able to deduce whether this transfer can be attributed to ARC or NRC. Appropriate test patterns must be used in order to determine the nature of the residual binocularity found in monofixation. It is tempting to speculate that the amount of interocular transfer found in monofixation is not just a coexisting condition, but that this represents the minimum amount of cortical binocular function necessary for peripheral fusion to maintain stable ocular alignment. This notion is supported by the recent results of Boman and Kertesz,[15] who studied fusional vergence responses in 11 strabismic subjects with small deviations. They found that while small central stimuli were not effective in producing fusional vergence responses, large extrafoveal stimuli subtending at least 10° of arc did produce fusional vergence responses in their strabismic subjects.

Normally, ocular alignment is maintained through fusional vergence eye movements, which are made in response to the retinal locations of the images in each eye. In order for the fusional vergence system to overlap the images onto corresponding retinal locations, the overall disparity between the two images must be detected and minimized. This could be accomplished if the visual system spatially filtered each image so that it loses its fine detail, thus allowing the two coarse images to be matched and then superimposed by vergence movements.[16,17] This would require a binocularity at least for those neurons transmitting the coarse image (i.e., those responding to low spatial frequency stimulation), which we found in subjects with the monofixation syndrome. If the above analysis is correct, then one could conclude that the maintenance of ocular alignment ought to be possible provided that the neurons responding to low spatial frequencies, or large receptive fields, are functionally binocular. Thus, those strabismics who do show MAE transfer with large coarse gratings probably have the potential for sufficient binocular cooperation to permit stable ocular alignment after their eyes are aligned.

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References

1. Hubel DH, Wiesel TN. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. J Physiol (London) 1962; **160:**106–154.
2. Hubel DH, Wiesel TN. Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. J Neurophysiol 1965; **28:**229–289.
3. Poggio, GF, Fischer B. Binocular interaction and depth sensitivity in striate and prestriate cortex of behaving rhesus monkey. J Neurophysiol 1977; **40:**1392–1405.
4. Hubel DH, Wiesel TN. Brain mechanisms of vision. Sci Am 1979; **241(3):**150–162.
5. Enroth-Cugell C, Robson JG. Functional characteristics and diversity of cat retinal ganglion cells. Invest Ophthalmol Vis Sci 1984; **25:**250–267.
6. Lehmkuhle SW, Fox R. Effect of binocular rivalry suppression on the motion aftereffect. Vision Res 1975; **15:**855–859.
7. O'Shea RP, Crassini B. Interocular transfer of the motion after-effect is not reduced by binocular rivalry. Vision Res 1981; **21:**801–804.
8. Blake R, Overton R. The site of binocular rivalry suppression. Perception 1979; **8:**143–152.
9. Keck MJ, Price RL. Interocular transfer of the motion aftereffect in strabismus. Vision Res 1982; **22:**55–60.
10. Price RL, Keck MJ. Motion aftereffect transfer in the monofixation syndrome. J Pediatr Ophthalmol Strabismus 1982; **19:**69–74.
11. Wolfe JM, Held R. A purely binocular mechanism in human vision. Vision Res 1981; **21:**1755–1759.
12. Wolfe JM, Held R. Binocular adaptation that cannot be measured monocularly. Perception 1982; **11:**287–295.
13. Wolfe JM, Held R. Shared characteristics of stereopsis and the purely binocular process. Vision Res 1983; **23:**217–227.
14. Mohn G, van Hof-van Duin J. On the relation of stereoacuity to interocular transfer of the motion and the tilt aftereffects. Vision Res 1983; **23:**1087–1096.
15. Boman DK, Kertesz AE. Fusional responses of strabismics to foveal and extrafoveal stimulation. Invest Ophthalmol Vis Sci 1985; **26:**1731–1739.
16. Marr D, Poggio T. A computational theory of human stereo vision. Proc R Soc Lond (Biol) 1979; **204:**301–328.
17. Marr D. Vision, a Computational Investigation into the Human Representation and Processing of Visual Information. San Francisco, W. H. Freeman & Co, 1982.