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## Positional acuity in amblyopia: does a perceptual consequence of neural recruitment exist?

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### Summary

Animal models of amblyopia have shown that visual deprivation for even brief periods can result in dramatic changes in cortical architecture. Active neural recruitment mechanisms present the possibility that the non-deprived eye of amblyopes may show enhanced visual capacity. This idea was tested by measuring a form of positional acuity which we have termed alignment threshold. Three subject groups were examined, adults, visually normal children, and children with amblyopia in which the non-deprived eye was tested. Alignment thresholds in adults were significantly better (~0.3 log unit) than the thresholds for visually normal children. No significant difference was found in thresholds between the visually normal children and the non-deprived eye of the amblyopic children. The results of this study suggest that subjects with unilateral amblyopia do not show enhanced visual alignment performance in their non-deprived eye. © 1998 The College of Optometrists. Published by Elsevier Science Ltd. All rights reserved

### Introduction

Since the pioneering studies on the effects of monocular deprivation carried out by Hubel and Wiesel (Wiesel and Hubel, 1963a,b; 1965; Hubel and Wiesel, 1963) over three decades ago, a substantial body of literature has documented the anatomical, physiological and behavioural consequences of this paradigm. This work has been crucial in the development of our understanding of the plasticity of the eye/brain system. One of the principal findings of animal studies is that at a cortical level, the deprivation of normal visual stimulation to one eye, for even brief periods, can result in a marked reduction in the ability to activate cortical neurones connected with that eye (Hubel and

Wiesel, 1970; Olson and Freeman, 1975; Freeman and Olson, 1979).

Perhaps surprisingly, functional impairments resulting from monocular deprivation are not accompanied by areas of unresponsive cortex. Physiological and anatomical techniques have shown in both cats and monkeys that the shrinkage of the ocular dominance columns receiving input from the deprived eye are paralleled by a marked expansion of the columns in the normal eye (Kratz *et al.*, 1976; Hubel *et al.*, 1977; Mitchell and Timney, 1984; Blakemore and Vital-Durand, 1986). This finding points to the existence of an active process of neural reconnection of the cortical pathways, where cells primarily responsive to one eye become responsive to the fellow eye following a lack of adequate visual input. This raises the interesting possibility that since the projections to the cortex from the non-deprived eye are now more extensive (Hubel *et al.*, 1977), one might expect this eye to show enhanced visual sensitivity.

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The pattern of normal visual maturation is characterised by an initial overproduction of neurones and superfluous axon arborisation. This process is proceeded by selective eradication of a substantial number of axons and early connections (Rakic, 1986; Rakic and Riley, 1983). Several studies have shown that unilateral enucleation during visual maturation can have a dramatic effect on this process in the remaining eye. Significantly, the normal process of retinal ganglion cell death is impeded with the consequential retention and perhaps expansion of their central connections (Rakic, 1986; Guillery, 1989; Lund *et al.*, 1973). Therefore, the remaining eye may not only benefit from increased cortical space but it may possibly have more retinal ganglion cells at its disposal.

Studies examining human psychophysical correlates of the anatomical and physiological changes reported in the animal models have produced vastly conflicting results. Subjects who have undergone early unilateral enucleation have been found to display superior contrast sensitivity thresholds when compared to normal binocular subjects tested monocularly (Freeman *et al.*, 1989) and binocularly (Nicholas *et al.*, 1996). Supra-normal Vernier acuity in the non-amblyopic eye of unilateral amblyopes has also been reported previously (Freeman and Bradley, 1980; Rentschler and Hilz, 1985). However, other studies have failed to reveal any enhanced visual capability for this form of hyperacuity in the non-deprived eye of both amblyopes (Johnson *et al.*, 1982) and subjects who have had an eye enucleated at an early age (Gonzalez *et al.*, 1992). These contradictory findings are further confounded by the suggestion that the dominant eye of amblyopes may, in fact, even be abnormal (Kandel *et al.*, 1976, 1980).

Many of the studies investigating possible differences in visual performance between normal eyes and the non-deprived eyes in monocular and amblyopic subjects have employed Vernier acuity tasks (Freeman and Bradley, 1980; Rentschler and Hilz, 1985; Johnson *et al.*, 1982) in conjunction with sophisticated psychophysical procedures (Freeman and Bradley, 1980; Johnson *et al.*, 1982; Rentschler and Hilz, 1985) on relatively few trained adult subjects (Rentschler and Hilz, 1985; Johnson *et al.*, 1982; Osuobeni, 1992). A Vernier acuity task is often chosen since the human visual system demonstrates an acute ability to locate the relative position of objects within the visual field. This clear superiority over anatomically-limited resolution thresholds has elicited the term 'hyperacuity' to describe this set of spatial thresholds (Westheimer, 1975). Thresholds in the hyperacuity range clearly require some form of neural processing beyond the level of the photoreceptors, so they might be expected to vary as a function of the neural mechanisms available for post-receptoral processing.

The aim of this study was to use a simple, clinical test of hyperacuity, to investigate differences in visual performance between adults, normal binocular children and the non-deprived eye of amblyopic children. The psychophysical test employed is similar to the hyperacuity gap test described by Enoch and his co-workers (Enoch and Williams, 1983; Enoch *et al.*, 1988).

## Methods

### Subjects

Three subject groups were investigated: a group of previously untreated unilateral amblyopic children ( $n = 20$ , mean age =  $5.73 \pm 1.97$  years), exhibiting a range of sensory deficits (five strabismic, nine anisometropic, six strabismic and anisometropic); a group of visually normal children ( $n = 18$ , mean age =  $5.94 \pm 1.14$  years); and a control group of visually normal adults ( $n = 21$ , mean age =  $22.32 \pm 2.7$  years). Informed consent was obtained from the adults and parents of all children prior to experimental testing.

### Procedure

Alignment thresholds were measured in the dominant eye (this was defined as the eye with the best visual acuity) of the adult and the normal child groups, and in the non-deprived eye of the amblyopic group using a 5-dot bisection task. This was generated on the CRT (HP,  $640 \times 480$  pixels) of an HP-386 PC. The target configuration consisted of four outer bright dots and a central dot (luminance of all dots  $187 \text{ cdm}^{-2}$ ). The central dot was decentered randomly and the subject was required to adjust its position, using a joystick controller, to the perceived centre of the pattern described by the four surrounding dots (see *Figure 1*).

This process allows a simultaneous assessment of both horizontal and vertical alignment thresholds. Since positional thresholds vary as a function of the vertical and horizontal separation between the stimulus features (Westheimer and McKee, 1977; Enoch and Williams, 1983), a single measure of alignment threshold does not provide a comprehensive assessment of performance. In a visually normal subject, when the stimulus features are closely spaced, the targets cannot be resolved as being spatially separate. Thus at small gap separations, performance on the task is limited by blur and contrast. As the gap between the stimulus features is increased a range of thresholds are generated. With increasing gap size, the ability to make a judgement on relative alignment becomes increasingly difficult, and poorer thresholds are obtained (Westheimer and McKee, 1977; Enoch

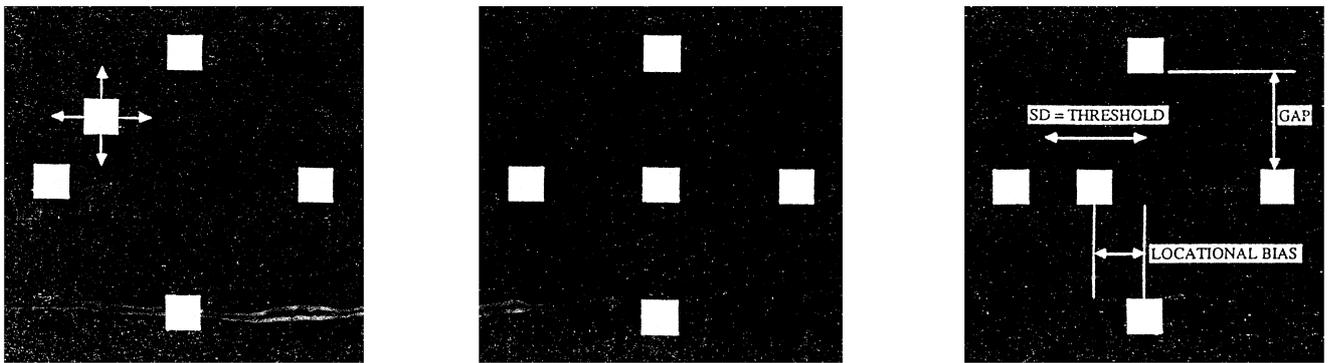


Figure 1. Schematic diagram of the stimulus configuration used to measure alignment thresholds.

and Williams, 1983). This has been termed the feature separation effect. The optimal gap size can be estimated from the visual acuity score. This procedure reduces test administration time and eliminates the testing of gap separations which are unlikely to yield useful information. A minimum of five gap separations ranging from 6.4–80 min of arc were investigated in a pseudo-random sequence.

For any psychophysical test to be applied successfully to a young population in a clinical environment relevant information must be collected rapidly, which often precludes the use of sophisticated psychophysical procedures. A method of adjustment was chosen as it has been shown to reduce test times and yields results in this type of task which are not significantly different from a more sophisticated modified staircase technique (Lakshminarayanan *et al.*, 1992).

The procedure of re-aligning the central dot was repeated four times at each gap separation in both adult and child subjects. The variability (standard deviation) exhibited by a subject on repeated trials is taken as a measure of alignment threshold and the mean value of subjective alignment (mean error) indicates the locational bias.

Subjects wore appropriate refractive corrections and were seated at a distance of 4 m from the screen. A clinical ophthalmological examination was conducted on all subjects to rule out the presence of visual pathway disease which may influence thresholds. All subjects were naive as to the purpose of the experiment, the comparison between groups being made under identical experimental conditions, with each subject being given one practice run at a large gap separation (60 arcmin) to familiarise themselves with the test. Visual acuity was recorded on all patients using the LogMAR Crowded Test (Keeler Ltd., UK; McGraw and Winn, 1993). This test is quick and easy to perform and provides an accurate and reliable measure of visual acuity in both adults and children (McGraw *et*

*al.*, 1993). This chart is described in detail elsewhere (McGraw and Winn, 1993).

**Results**

*Visually normal adults versus visually normal children*

The mean visual acuity of the adult group was  $-0.09 \pm 0.08$  LogMAR (logarithm of the minimum angle of resolution) score (approximately 6/4.75 Snellen equivalent) while that of the visually normal children was  $0.07 \pm 0.09$  LogMAR score (approximately 6/7.5 Snellen equivalent). This difference in acuity scores between the two groups was found to be statistically significant ( $p < 0.005$ ) and is likely to be due to a combination of the effects of contour interaction, which the LogMAR Crowded Test seeks to maximise, and attentional differences. The deleterious effects of contour interaction have been shown to be

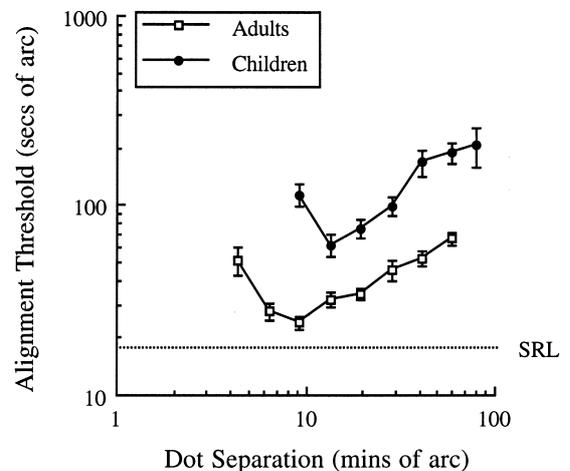


Figure 2. Comparison of horizontal alignment thresholds between the visually normal children and adults. Error bars are SEMs.

greatest in childhood and gradually reduce with normal visual development (Atkinson *et al.*, 1985).

Horizontal alignment thresholds for the adults and visually normal children are shown in *Figure 2*.

The adult group obtained an optimum horizontal alignment threshold of  $24.14 \pm 1.77$  arcsec at a dot separation of 9.3 arcmin. The normal children obtained an optimum horizontal threshold of  $61.77 \pm 8.53$  arcsec but at a dot separation of 13.5 arcmin. A repeated measures ANOVA with one between subjects factor (age) and one within subjects factor (separation) revealed that the thresholds for the two different age groups were significantly different ( $F_{1,37} = 86.132$ ,  $p < 0.0001$ ) and that the dot separation of the targets had a significant effect on thresholds ( $F_{5,185} = 22.831$ ,  $p < 0.0001$ ).

A similar result was obtained for vertical alignment thresholds with the adult group obtaining an optimum vertical alignment threshold of  $24.39 \pm 2.02$  arcsec at a dot separation of 9.3 arcmin, while the children obtained an optimum vertical threshold of  $65.08 \pm 7.00$  arcsec at a feature separation of 13.5 arcmin. Again, a repeated measures ANOVA with one between subjects factor (age) and one within subjects factor (separation) revealed that the thresholds for the two different age groups were significantly different ( $F_{1,37} = 276.721$ ,  $p < 0.0001$ ) and that dot separation of the targets had a significant effect on thresholds ( $F_{5,185} = 27.674$ ,  $p < 0.0001$ ).

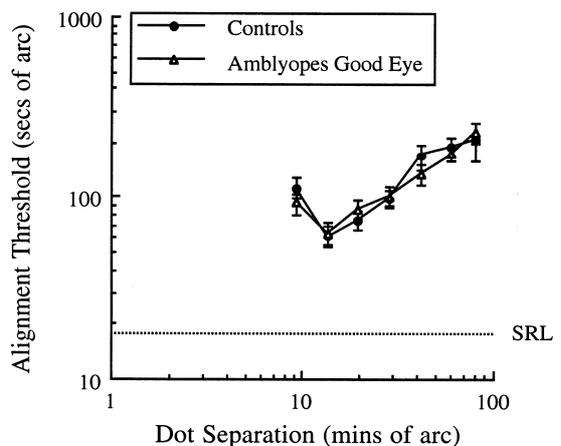
No significant difference was found between horizontal and vertical alignment thresholds for the adult (repeated measures ANOVA;  $F_{1,40} = 1.201$ ,  $p > 0.1$ ) or the child groups (repeated measures ANOVA;  $F_{1,34} = 0.716$ ,  $p > 0.1$ ). The dashed line on *Figures 2* and *3*, marked SRL (screen resolution limit), indicates the minimum angular displacement of the central dot i.e. the angular subtense of one pixel for the monitor used. As can be seen from *Figure 2* the adult group performs very close to the screen resolution limit for horizontal alignment tasks. This situation was also true for vertical alignment tasks.

#### *Dominant eyes of children with amblyopia versus visually normal children*

The mean visual acuity of the visually normal children was  $0.07 \pm 0.09$  LogMAR score while that of the dominant eyes of the amblyopic group was  $0.05 \pm 0.06$  LogMAR score (approximately 6/7.5 Snellen equivalent). This difference was not statistically significant ( $df = 36$ ;  $t = 0.02$ ;  $p > 0.1$ ).

Horizontal alignment thresholds for both the normal and amblyopic children are shown in *Figure 3*.

The optimum mean threshold for the dominant eyes of the amblyopes was  $64.52 \pm 9.38$  arcsec, achieved at



**Figure 3.** Comparison of horizontal alignment thresholds between the dominant eyes of the amblyopic group and the normal age matched control group. Error bars are SEMs.

a dot separation of 13.5 arcmin. The optimum mean threshold for the vertical alignment task was  $70.27 \pm 8.24$  arcsec for the amblyopic group at a dot separation of 13.5 arcmin.

As with the visually normal adults and children, no difference was demonstrated between horizontal and vertical alignment thresholds (repeated measures ANOVA;  $F_{1,38} = 0.827$ ,  $p > 0.1$ ). Furthermore, a repeated measures ANOVA with one between subjects variable (normal control or non-deprived eye of child with amblyopia) and one within subject factor (separation) revealed no significant difference in horizontal thresholds between the two groups ( $F_{1,36} = 0.433$ ,  $p > 0.1$ ). Again dot separation was found to have a significant effect on thresholds ( $F_{6,216} = 46.927$ ,  $p < 0.0001$ ). A similar result was obtained for vertical thresholds ( $F_{1,36} = 0.528$ ,  $p > 0.1$ ) with no significant difference in threshold demonstrated between the two groups. Similarly, dot separation was found to effect thresholds significantly ( $F_{6,216} = 53.258$ ,  $p < 0.0001$ ).

All children managed to perform the hyperacuity test successfully and were able to complete the task in approximately 3 min.

#### **Discussion**

The results of this study show that normal children and adults display alignment threshold functions which are broadly similar in shape, with the children demonstrating an increase in threshold of approximately 0.35 log unit. This threshold deficit is similar in magnitude to deficits reported between children and adults for contrast perception (Bradley and Freeman, 1982). It is interesting to speculate whether this difference reflects a manifestation of a developing visual system. If one could conclude that the threshold

differences obtained between the child and adult groups indicated neural immaturity this would convey important implications for developmental periods of visual sensitivity and for the treatment of conditions such as strabismus and amblyopia, since the basis of treatment depends critically upon a sound knowledge of normal visual development.

However, it is impossible to filter out non-visual factors which may contribute to reduced performance in the present positional acuity task. Major non-visual factors which require consideration are the motor maturity of the children in positioning the joystick and their capacity to attend to and concentrate sufficiently on the task. In simulated conditions of inattention, measured contrast perception thresholds in adults were found to differ by 0.3 log unit (Bradley and Freeman, 1982), a magnitude similar to the discrepancy in alignment thresholds found between children and adults in the present study. Since the determination of alignment thresholds involves task repetition over a number of trials, the effects of practice on positional acuity thresholds also play an important role. Practice effects are known to improve performance considerably in adult subjects on relative localisation tasks (McKee and Westheimer, 1978), and it is conceivable that such effects may be reduced in younger children. Therefore, it is possible that non-visual factors impose a procedural limit to alignment thresholds in young children. Nonetheless, the possibility that the threshold difference found between adults and children reflects a combination of both visual and neural factors cannot be ruled out. Many processes involved in normal visual development may still be active in the age group of children investigated in this study. For example, synaptogenesis in the visual cortex is known to be most rapid between the ages of 2–4 months and from 8 months to 11 years of age a process of synapse elimination is active resulting in a loss of almost 40% of all synapses (Huttenlocher *et al.*, 1982; Huttenlocher and De Courten, 1987).

The deterioration in spatial performance produced by appropriately positioned contours is termed contour interaction or visual crowding. This effect is ubiquitous in spatial vision and has been reported for a range of spatial tasks such as orientation discrimination (Westheimer *et al.*, 1976), Vernier acuity (Westheimer and Hauske, 1975; Levi and Klein, 1985), stereoacuity (Butler and Westheimer, 1978) and Snellen acuity (Flom *et al.*, 1963b). The effects of contour interaction are thought to be cortically mediated since they still occur when the target and flanking contours are presented contra-laterally (Flom *et al.*, 1963a). The significant difference in visual acuity scores found between children and adults supports previous reports that the impairment of spatial resolution result-

ing from flanking contours is more pronounced in childhood (Atkinson *et al.*, 1985). If the effects of contour interaction on positional acuity thresholds were stronger in children than adults, one would expect a horizontal shift to the right of the data from the child group. *Figure 2* shows such a shift. The difference between the gap separations at which optimum threshold was achieved was found to be significantly different in the visually normal children and the visually normal adults for both horizontal ( $df = 37$ ;  $t = 7.67$ ;  $p > 0.001$ ) and vertical ( $df = 37$ ;  $t = 6.17$ ;  $p > 0.001$ ) alignment tasks. *Figure 3* shows that no difference exists in the effects of contour interaction between the dominant eyes of the amblyopic group and the age-matched controls.

The results of the present study do not support the finding that the dominant eyes of amblyopes exhibit enhanced positional acuity over age matched, visually normal children. There are two possible explanations for this result. Firstly, it should be noted that the vast majority of data on cortical neural recruitment is derived from animal studies which have employed early monocular eyelid suture to produce visual pattern deprivation. This procedure mimics only the rarest form of deprivation amblyopia encountered by clinicians, such as that produced by unilateral congenital cataract. However, it is unclear whether the profound changes in cortical architecture reported in the animal studies also apply to the milder forms of amblyopia associated with anisometropia, strabismus or a combination of the two. Two recent studies have performed post-mortem examination of striate cortex obtained from human subjects with amblyopia associated with accommodative strabismus (Horton and Hocking, 1996) and anisometropia (Horton and Stryker, 1993). In both cases no shrinkage of the ocular dominance columns related to the amblyopic eye were found. This suggests that milder forms of amblyopia develop at a time when the cortex has matured sufficiently to ensure that the ocular dominance columns are immune to the shrinkage normally induced by early visual deprivation. It should be noted, however, that these studies are single case reports and that the pattern of ocular dominance columns in humans can be quite variable (Horton and Hedley-White, 1984; Horton *et al.*, 1990). Therefore, no firm conclusions can be made until this finding is confirmed in other cases.

An alternative explanation may be that a process of neural recruitment does occur in humans, but that the signal which is to be sampled at the cortex is attenuated elsewhere in the visual pathways. Neural recruitment would be expected to reveal enhanced visual function if task performance is limited by the density of responding cells in the visual cortex. In this situation the increased cortical area available to the non-

deprived eye may result in no net gain in cell density. Furthermore, many parameters of visual function are not cortically limited, for example foveal visual acuity is limited not by cortical sampling but by the low pass filtering imposed by the optical system of the human eye and the physical spacing between the foveal photoreceptors. It has also been shown that the visibility of sinusoidal gratings may be limited by similar factors (Banks *et al.*, 1987). The high frequency roll-off of the foveal contrast sensitivity function for gratings with a fixed number of cycles can be explained by the operation of pre-neural factors alone (Banks *et al.*, 1987). In these situations neural recruitment, resulting in an increase in cortical sampling, will be of little benefit. While hyperacuity tasks are clearly not limited by the optical transfer function of the human eye or the centre-to-centre spacing of foveal photoreceptors, the stage in the visual pathway which limits hyperacuity thresholds to their observed levels, remains as yet undetermined. However, modern models of hyperacuity concern themselves with mechanism sensitivity, particularly the differential response of filters to positional tasks (Wilson, 1986; Regan and Beverley, 1983; Klein and Levi, 1985) rather than concentrating on an extremely fine sampling network as a means of obtaining hyperacuity thresholds.

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