VISUAL DEVELOPMENT AND PLASTICITY IN CHILDREN

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ABSTRACT

The effects of visual experience on perception were examined using two classic research paradigms: visual deprivation and perceptual adaptation. The present study evaluates the extent to which children in the 5- to14-year-old age range have the capacity for visual plasticity with respect to recovery from the effects of astigmatism-related visual deprivation and adaptation to spatially distorted visual input.

Visual experience was altered through eyeglass correction of astigmatism, a condition of the eye that induces degraded (blurred) visual input and causes a form of visual deprivation. Lenses that correct astigmatism cause two changes in sensory input: they alleviate the deprivation effects of astigmatism, and cause spatial distortion. Perception was initially measured when the children first received eyeglass correction, and change in perception was measured after 1 month of wear, and after 1 year of wear. Measures included recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, stereoacuity, and form perception.

Baseline analyses of normal (non-astigmatic) subject data indicated that recognition acuity, resolution acuity, vernier acuity, and contrast sensitivity continue to develop within the 5- to 14-year-old age range. Baseline analyses also revealed that children who experienced astigmatism-related deprivation demonstrated perceptual deficits, in comparison to non-astigmatic children, on all measures of perception (although deficits within some measures depended on stimulus orientation (grating acuity and contrast sensitivity) and spatial frequency of the stimulus (for contrast sensitivity)),

and demonstrated measurable distortions in form perception. However, primary outcome analyses revealed little evidence of plasticity with regard to recovery from the effects of deprivation and no evidence of plasticity with regard to perceptual adaptation to distortion.

The results suggest that children in the 5- to 14-year-old age range may be beyond the sensitive period for recovery from astigmatism-related deprivation through simple restoration of clear visual input. Discussion focuses on theoretical views on conditions necessary for plasticity (Bedford, 1993a, 1993b, 1995, Banks, 1988), and their implications regarding another intervention, discrimination learning, that might be more effective at inducing plasticity in children and adults who are beyond the sensitive period for plasticity, and their implications for interpretation of data on adaptation to spatial distortion observed in the present study.

1. INTRODUCTION

Visual plasticity, defined here as the capacity of the human visual perceptual system to change based on visual perceptual experience, is a key component in the development and maintenance of a perceptual system that allows for consistent, accurate, and efficient perception and interaction with our environment (Bedford, 1999, Gibson and Pick, 2000). The experimental psychology and clinical vision literatures provide a wealth of examples of how the human visual/perceptual systems adapt based on information gleaned through visual experience.

The research presented here is based on two classic research paradigms used to study human visual plasticity. The first paradigm, used primarily in the clinical vision literature, is the visual deprivation paradigm. The second paradigm, used primarily in the experimental psychology literature, is the perceptual adaptation paradigm. The study reported here asks to what extent children in the 5- to 14-year-old age range have the capacity for visual plasticity with respect to recovery from the effects of visual deprivation and with respect to adaptation to spatially distorted visual input. As I will explain in the introduction that follows, answers to these questions will begin to fill significant gaps in both the clinical vision and the experimental psychology literatures, and will make an important step towards linking research and theory on visual plasticity across these two literatures that have remained largely separate.

The visual deprivation paradigm has been widely used to evaluate the effects of experience on visual development. Over the past few decades, this form of research has provided extremely valuable insights into the organization of the visual system, mechanisms of visual perception, and the variables influencing visual development. Studies employing the visual deprivation paradigm reflect the results of developmental plasticity under abnormal circumstances: under conditions of visual deprivation, visual perceptual systems of infants and young children develop abnormally in comparison to development of visual perception when clear visual input is present during development. This pattern of results suggests that typical visual experiences during development are a necessary component of normal visual/perceptual development, and visual deprivation studies help us better understand the nature of the visual experiences that are necessary for normal development of perception.

Because inflicting prolonged deprivation upon human subjects has the potential to do permanent harm to perceptual systems, particularly if subjects are young children, most deprivation studies have been conducted with animal subjects. However, the clinical vision literature has documented some naturally occurring abnormalities and variations of the human visual system that can induce various forms of visual deprivation, and the occurrence of these conditions provides researchers and clinicians with unique opportunities to better understand the effects of deprivation and alleviation of the deprivation on development and plasticity in the human visual system.

Studies of patients with various naturally occurring conditions that degrade the quality of visual input to the visual system have shown that individuals who experience deprivation during early development often demonstrate abnormal visual perceptual experiences immediately following restoration of clear visual input, indicating that that effects of the deprivation of clear visual input result in a reduction in our perceptual abilities (e.g., Maurer and Lewis, 1993). Another example of visual plasticity that also comes from the clinical vision literature is plasticity associated with *recovery* from the effects of visual deprivation. These studies show that while individuals typically demonstrate reduced perceptual abilities after being deprived of clear visual input, they often demonstrate gradual improvement in visual perceptual functioning once clear input is introduced, particularly when normal input in introduced early in development (e.g., Maurer and Lewis, 1999).

The present study addresses plasticity associated with recovery from the effects of visual deprivation caused by an ocular condition called *astigmatism*. Astigmatism is a condition of the cornea and/or lens of the eye that, when uncorrected, induces blurred vision. Fortunately, the deprivation of clear input caused by astigmatism can be corrected through routine prescription of appropriate eyeglass correction. However, previous research has shown that when astigmatism remains uncorrected during early development, individuals experience visual perceptual deficits that persist even after the cause of the deprivation, astigmatism, is corrected or alleviated with corrective lenses (Freeman, Mitchell, Millodot, 1972, Mitchell, Freeman, Millodot, and Haegerstrom, 1973). Thus, while the deprivation of clear input induced by uncorrected astigmatism is optical in origin (i.e., it is caused by abnormalities of the optics of the eye which prohibit the focus of clear images on the retina), the deficits that persist *after the astigmatism is corrected* reflect the capacity of plasticity of the visual perceptual system as a result of the deprivation. These deficits are believed to be perceptual/neural in origin because they are apparent even when the structural properties of the eye appear to be intact, and even after appropriate eyeglass correction provides clear focus of images on the retina.

The research presented here focuses on plasticity in children between the ages of 5 and 14 years. This age group was chosen because previous research from the clinical vision literature has suggested that there is a sensitive period for plasticity associated with visual deprivation and recovery from the effects of visual deprivation. There are only limited data regarding the upper age limit of the sensitive period for plasticity associated with recovery from the effects of astigmatism-related deprivation in humans. One of the primary goals of this study is to determine the extent to which plasticity still exists in the visual system of 5- to 14-year-old children in terms of recovery from the effects of astigmatism-related visual deprivation.

In addition to plasticity related to recovery from the effects of visual deprivation, the present study also assesses the capacity for another form of visual plasticity, perceptual adaptation, in the same subjects. Perceptual adaptation has been defined by Welch (1978) as "a semi permanent change of perception or perceptual-motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors in behavior induced by this discrepancy". For over 100 years, perceptual adaptation studies have provided important information regarding the ability of our perceptual systems to change as a result of detection of perceptual discrepancies. The ability of our visual system to adapt in this manner allows us to maintain accurate perception despite changes due to growth (Held, 1965, Bedford, 1999), and allows us to correction for "perceptual drift", i.e., gradual changes in perception that may occur over time and require realignment (Bedford, 1999).

As I will describe in more detail in the sections that follow, lenses that correct the eye for astigmatism, cylinder lenses, cause two changes in sensory input. First, as previously noted, they remove the deprivation effects of astigmatism by allowing the eye to focus images clearly on the retina. Second, they have spatially distorting effects that can alter both monocular and binocular spatial perception. In the study that follows, I will assess the extent to which children adapt to the spatial distortion perceived when cylinder lenses are first worn. Previous research on adult subjects has indicated that extended wear of such lenses result in some, but not complete adaptation to the spatial distortion (Mack and Quartin, 1974, cited in Welch, 1978). However, previous studies were conducted with adult subjects, leaving open the possibility that complete adaptation was not achieved because subjects were beyond the sensitive period for this form of adaptation. Thus, the present study will measure monocular form perception to evaluate adaptation to the spatial distortion induced by astigmatism lenses in the same sample of children for whom I will evaluated plasticity for recovery from the effects of visual deprivation. This data will be an important addition to the experimental psychology literature on perceptual adaptation, because the literature contains little data on adaptation in children, does not focus on sensitive periods, as the clinical vision literature on plasticity does.

Another research paradigm that has documented examples of human visual plasticity is the discrimination learning paradigm, which has traditionally been reported in the experimental psychology literature. Eleanor Gibson (1963, 1991) describes this form of plasticity, which she refers to as differentiation, as "any relatively permanent and consistent change in the perception of a stimulus array, following practice or experience with this array". In studies of discrimination learning, researchers have demonstrated that we can improve our abilities to discriminate fine differences between perceptual stimuli through practice and experience. This facility allows us to tailor our fine perceptual skills towards performance of perceptual tasks that are relevant to us, allowing for more precise perception of important stimuli and more efficient interaction with our environment (Gibson and Pick, 2000). The discrimination learning paradigm was not explicitly implemented in the present study. However, as I will discuss in more detail in the sections that follow, I believe that research on discrimination learning from the experimental psychology literature has important implications for research on other examples of visual plasticity, particularly plasticity associated with recovery from the effects of deprivation.

In summary, the primary goal of the present study is to examine plasticity in children with regard to recovery from the effects of astigmatism-related deprivation and with regard to perceptual adaptation to the spatially distorting effects of lenses that are used to correct astigmatism. Recovery from the effects of astigmatism-related visual deprivation will be assessed for several basic aspects of visual perception: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity. Previous research indicates that there may be different sensitive periods associated with different perceptual functions with regard to deprivation and recovery (e.g., Harwerth, Smith, Duncan, Crawford, and von Noorden, 1986, Levi and Carkeet, 1993), and thus there may be differences in the extent to which each function can recover from the effects of deprivation. Plasticity as it relates to perceptual adaptation will be assessed for monocular form perception. In contrast to the clinical vision literature, the literature on perceptual adaptation has not experimentally addressed the issue of sensitive periods and studies of adaptation in children are extremely rare. The present study is unique in that it evaluates plasticity for adaptation to spatial distortion in children, and allows for comparisons in the extent to which children show plasticity for recovery from deprivation and for perceptual adaptation.

To briefly preview the design of the present study, perception will be measured when the children first receive their eyeglass, after 1 month of eyeglass wear, and after 1 year of eyeglass wear. The experimental manipulation consists of altering visual experience through eyeglass correction of astigmatism. This manipulation results in two changes in sensory input: alleviation of the deprivation effects of astigmatism by allowing the eye to focus clear images on the retina, and spatial distortion. Primary analyses will focus on evaluation of perceptual change over 1 month and over 1 year for children with high astigmatism in comparison to a control group of children with little or no astigmatism. The fact that the same method (same pair of eyeglasses) alters visual experience for each of these different perceptual functions allows for direct comparisons in plasticity observed based on equivalent amounts of visual perceptual experience across different measures of perception.

While the primary goal of this study is to determine if plasticity occurs as a result of the eyeglass intervention in children, the baseline measures of perception will also provide a wealth of information to the literature on developmental changes in perception in normally sighted children, the effects of astigmatism-related deprivation on different aspects of visual perception, and on perception of spatially distorted visual input in children in the 5- to 14-year-old age range. With regard to baseline data on normally sighted children, the data obtained in the present study are unique in that they include measures on a large sample of children across a variety of perceptual measures in an age range that is less frequently examined in developmental studies of vision (most developmental studies of vision focus on infants and young children, as those periods encompass the most rapid periods of visual development). While some data on the effects of astigmatism-related deprivation exist in the literature, the data obtained in present study are unique in reporting results from a large sample of astigmatic children for which measures of on a wide variety of perceptual abilities were obtained. These data will provide a broad description of the effects of astigmatism-related deprivation on visual development not previously available in the literature. Thus, a secondary goal of the present study is to closely examine baseline measures, both for children with astigmatism and for children without astigmatism, in order to gain better insight into normal visual development in this 5- to 14-year-old age range, and abnormal visual development associated with astigmatism-related deprivation.

In the sections that follow, I discuss in more detail what is currently known about the effects of astigmatism and cylinder lenses on visual perception and on visual development. I will begin with a brief discussion of astigmatism, and will describe the effects of uncorrected astigmatism on perception, and the effects of cylinder lenses on perception. Finally, I summarize the existing evidence for plasticity associated with deprivation due to astigmatism, plasticity associated with recovery from the effects of deprivation due to astigmatism, and plasticity associated with adaptation to spatial distortion.

1.1 The Effects of Uncorrected Astigmatism on Visual Perception

In this section, I discuss in greater detail the nature of the visual deprivation induced by uncorrected astigmatism. Regular astigmatism is a condition of the cornea and/or the lens of the eye in which there is unequal curvature across meridia (i.e., orientations) (Rosenfield, 1988). For example, the surface of a non-astigmatic cornea or lens is shaped like the surface of a basketball, with equal curvature across directions, whereas the surface of an astigmatic cornea or lens is shaped somewhat like the surface of football in which the curvature in one direction is steeper than the curvature in the orthogonal direction. This unequal curvature affects the refraction of light as it enters the eye, and influences the quality of images projected on the retina. The effects of astigmatism on vision are particularly disruptive because, unlike common conditions such as myopia (nearsightedness), in which distance vision is disrupted but clear vision at near is often preserved, and high hyperopia (farsightedness) in which near vision is disrupted but distance vision is often preserved, individuals with astigmatism do not receive clear visual input at distance or at near.

Fortunately, like hyperopia and myopia, ophthalmologists and optometrists can correct for the optical defocus caused by astigmatism by prescribing lenses. These lenses, called cylinder lenses, have unequal curvature across different orientations. With proper prescription, they can correct the unequal refraction of the light that is caused by the astigmatism and improve the quality of the images the eye receives by allowing the eye to focus images clearly on the retina.

Before I discuss how astigmatism might effect visual development, I will begin with a demonstration of what astigmatic individuals might experience when astigmatism is uncorrected, i.e., a demonstration of how the world may look through an astigmatic eye. These examples provide a sense of the type of visual deprivation experienced by individuals with astigmatism. Examples are provided in Figure 1. Imagine that the images of the spoked wheel, the letter acuity chart and the single line on the letter acuity chart on the left are the stimuli that the observer is viewing. The images on the right are simulations of what an observer with uncorrected astigmatism might perceive when viewing these stimuli. These examples illustrate an important feature of astigmatism-induced deprivation: the observer may perceive differences in resolution acuity (the ability to discriminate fine detail) for lines of different orientations. For example, notice that the vertical lines are most in focus, and the greatest amount of defocus occurs in the horizontal lines. As I will now explain in more detail, the orientation of the lines that are most in focus or out of focus in the presence of uncorrected astigmatism is dependent on the axis of the astigmatism (direction of most/least curvature), and the type of astigmatism present.

Stimuli

Simulated View through

Astigmatic Eye

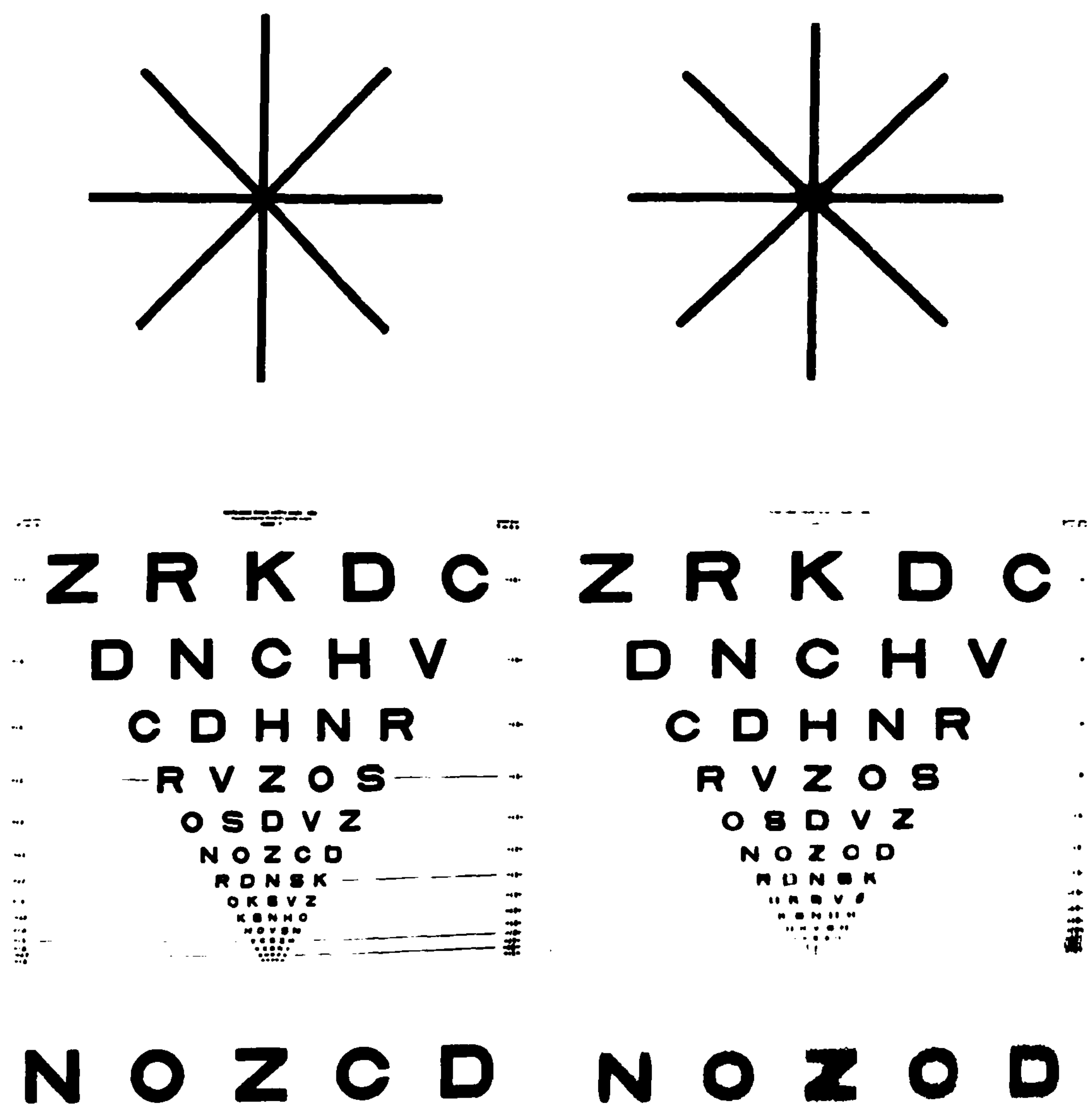


Figure 1. Demonstration of perception with astigmatic eye. Stimuli on the left represent viewed stimuli, stimuli on the right simulate stimuli as perceived by someone with uncorrected astigmatism.

The graphic in Figure 2 (revised from Gwiazda et al., 1985) provides an example of how the optical properties of astigmatism influence resolution acuity for lines of different orientations. The examples provided in this figure are particularly relevant the study that follows because these examples illustrate a certain type of astigmatism, i.e., with-the-rule astigmatism, in which the greatest curvature occurs in the vertical meridian and the least curvature occurs in the horizontal meridian (i.e., as if you were looking at a football lying on its side, with pointed ends facing to the right and left). Since all of the astigmatic subjects in the present study have with-the-rule astigmatism (i.e., the front of the cornea is most steeply curved in the vertical direction), the examples I use here focus on this form of astigmatism.

Imagine that each eye in Figure 2 is viewing a "+" stimulus (a horizontal and vertical line). In each example, the diagram of the eye illustrates at what point, relative to the retina, each line of the "+" comes into focus. For images that come into focus on the retina, the result is typically perception of a clear non-blurred image. For images that come into focus either in front of or behind the retina, the result is typically perception of a blurred image.

In a non-astigmatic eye both the horizontal and vertical lines of the "+" will come in focus in the same location: The + may come in focus on the retina (2a), in front of the retina (2b, myopic or nearsighted), or behind the retina (2c, hyperopic or farsighted). Regardless, in all three examples, both the horizontal and vertical lines come into focus at the same point, so both are equally in focus (2a) or equally out of focus (2b and 2c). Also

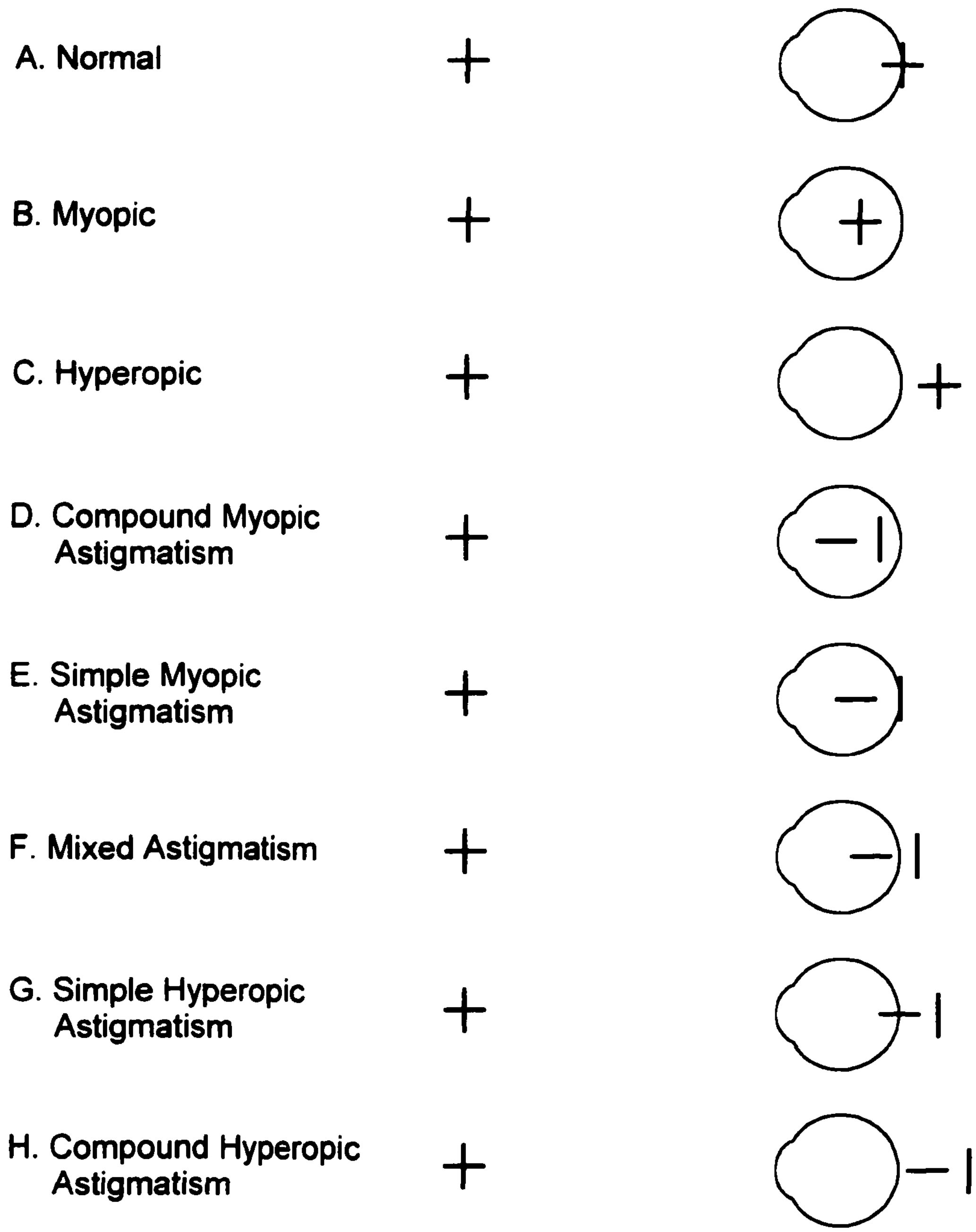


Figure 2. Schematic drawings of visual focus with astigmatic eye. Illustrations of the location at which the horizontal and vertical lines come into focus with respect to the retina for different types of with-the-rule astigmatism.

note that the hyperopic eye, with changes in accommodation (i.e., changes in the shape of the eye's lens), can bring the stimulus into focus when viewed at near or at distance. Changes in accommodation can not improve the clarity of the stimulus in myopia, but through changes in viewing distance (bringing the stimulus closer), the myopic eye can bring the stimulus into focus on the retina. Thus in these three examples, the observers gain visual experience with clear visual input under certain viewing circumstances, and their visual experience for stimuli across orientations is equivalent.

I now turn to examples of astigmatic eyes (Figure 2d-2h). In an uncorrected astigmatic eye, lines of different orientations come into focus at different locations with respect to the retina. Individuals with astigmatism can not bring both lines into focus *at the same time* through accommodation or through changes in viewing distance. However, depending on the type of astigmatism and the distance of the object being viewed, most astigmats are able to bring lines of individual orientations into focus under the right viewing conditions. This fact, which I will explain in further detail, makes predictions regarding the effects of astigmatism-related deprivation somewhat complicated.

In general, there are five types of astigmatism with respect to the focus of stimuli relative to the retina: simple myopic, compound myopic, mixed, simple hyperopic, and compound hyperopic. I begin with a discussion of the visual experience of individuals with myopic astigmatism. In individuals who have myopia without astigmatism (near-sighted) distant lines of all orientations are focused in front of the retina (see Figure 2b). Individuals with myopic astigmatism see distant lines of some orientations better than others (see Figures 2d and 2e). Since we relax our accommodation to get our best focus of distant objects, myopes can not improve focus through accommodation, but can induce better focus through changes in viewing distance. For example, depending on the amount of myopia, a myopic astigmat can adjust viewing distance to bring certain lines into focus, but can not bring all lines into focus at any one viewing distance. In general, however, the stimulus orientation that is furthest in front of the retina (most myopic, horizontal lines in our example) is more consistently out of focus for myopic astigmats. Thus, myopic with-the-rule astigmats experience more consistent deprivation for horizontal stimuli.

Mixed astigmats have one orientation in focus beyond the retina (hyperopic) and one focused in front of the retina (myopic) (Figure 2f). As previously noted in the case of myopic astigmats, at some distances, mixed astigmats will be able to see lines consistent with the myopic focus clearly, although this may occur relatively infrequently. Mitchell et al. (1973) assumed that mixed astigmats routinely accommodate to the hyperopic focus, as they can not accommodate to the myopic focus. This accommodation, while improving focus for the more hyperopic orientation, would further degrade focus for the more myopic orientation. Thus, it is likely that mixed with-the-rule astigmats, like myopic with-the-rule astigmats, experience more consistent deprivation for horizontal stimuli (more myopic focus) than for vertical stimuli (more hyperopic focus).

Finally, I turn to examples of hyperopic astigmatism. For individuals who are hyperopic and do not have astigmatism (far-sighted), stimuli come into focus behind the retina (see Figure 2c). Individuals with simple hyperopic astigmatism have one orientation (horizontal lines) in focus on the retina, and the orthogonal orientation (vertical lines) in focus behind the retina (see Figure 2g). For individuals with compound hyperopic astigmatism, vertical and horizontal lines are in focus behind the retina, but at different distances behind the retina (see Figure 2h, horizontal lines are better focus than vertical lines). Thus, one might assume that both simple and compound hyperopic astigmats might experience greater deprivation for vertically oriented stimuli, since stimuli of that orientation are furthest from focus on the retina. However, our ability to accommodate (adjust the shape of the lens) to compensate for moderate amounts of hyperopia makes this story more complicated. For example, individuals who are hyperopic and do not have astigmatism are generally able to bring near objects into focus by adjusting the shape of the lens in the eye through accommodation. Hyperopic astigmats also have this ability to accommodate, but the accommodation can not bring all lines into focus at the same time (i.e., they would need to accommodate different amounts to bring stimuli of different orientations into focus). Since we are interested in the nature of the visual deprivation that these individuals experience, an important question is how do these hyperopic astigmats accommodate? Do they routinely accommodate so that one line, perhaps the one closest to the retina, is in focus, or do they split the difference, and accommodate between the two extremes? The first scenario would predict greater deprivation for vertical lines, whereas the second would predict somewhat equivalent deprivation for both lines. Mitchell et al. (1973) assumed that hyperopic astigmats routinely accommodate to the least hyperopic focus (horizontal lines). Later, Freeman (1975) provided some support for this hypothesis. He measured accommodation in a subject with hyperopic astigmatism and found that the subject accommodated to focus the stimulus orientation corresponding to the least hyperopic meridian. However, recent evidence provided by Dobson, Miller, Harvey and Mohan (2002, in press) indicate that preschoolers with hyperopic astigmatism show equally reduced grating acuity for both horizontal and vertical stimuli, suggesting that they experience equivalent deprivation for both stimulus orientations during development. A study, similar in design to that conducted by Freeman (1975), in which we measure accommodation in a large sample of uncorrected astigmatic children is currently underway, and should provide evidence for patterns of accommodation in children with astigmatism, and provide further information regarding the nature of the deprivation experienced by hyperopic astigmats.

In summary, while it is clear that there are stimulus orientations that are more frequently out of focus for individuals with each type of astigmatism, the previous discussion highlights the fact that most astigmats do not experience *constant* deprivation of clear input for stimuli of any single orientation, and are likely to experience some degree of deprivation of clear input stimuli across orientations. Thus, the exact nature of the deprivation experience by each child, with regard to frequency and duration of deprivation for specific stimulus orientations, can not be clearly defined based on the available literature. For the purpose of the present study, however, I have generated predictions in accordance with previous theory and research on astigmatism-related deprivation in adult subjects (Mitchell et al., 1973, Freeman, 1975). More specifically, I predict that because the stimulus orientation that is furthest from focus on the retina (horizontal for myopic astigmats and vertical for hyperopic astigmats) or more myopic in the case of mixed astigmatism (horizontal) is the stimulus orientation for which subjects experienced the greatest and more consistent deprivation of clear visual input, and it is this stimulus orientation for which subjects should demonstrate reduce perceptual abilities once the astigmatism is corrected. Because the exact nature of astigmatism-related deprivation is still in question, the secondary goal of the present study with regard to baseline measures of the effects of astigmatism-related deprivation on visual development will make an important contribution to the literature, and may provide further insight into the exact nature of the deprivation experienced in subjects with different forms of astigmatism.

1.2 The Effects of Astigmatism-Related Deprivation on Visual Development

Thus far, I have only discussed the effects of uncorrected astigmatism on perception, i.e., the nature of the deprivation experienced due to the effects of poor optics induced by the presence of astigmatism. In this section, I turn to issues of plasticity, and ask what an astigmatic observer perceives when you provide her or him with the appropriate optical correction (eyeglasses) for correction of astigmatism, so that stimuli of all orientations are focused on the retina, as shown in Figure 2a. To briefly preview, some individuals with astigmatism perceive stimuli clearly when wearing the proper eyeglass correction. However, for individuals who had high astigmatism during early visual development, often clear vision and equal resolution acuity is not achieved for stimuli of all orientations even when the appropriate eyeglass correction for astigmatism is worn. Furthermore, the stimulus orientation for which visual deficits are apparent is consistent with the stimulus orientation for which the uncorrected astigmatism induced the greatest deprivation during development. In these situations, the observer is said to have *amblyopia*, a clinical term for reduced vision that can not be corrected simply through appropriate eyeglass correction. In addition, some astigmatic individuals show evidence of a sub-type of amblyopia, *meridional amblyopia,* defined by a *difference* in acuity across stimuli of different orientations that cannot be corrected with eyeglasses.

In this section I summarize the literature on the effects of astigmatism-related deprivation on visual development, and plasticity as it pertains to recovery from the effects of astigmatism-related deprivation for five measures of perception included in the present study: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity. For each visual perceptual function, I will describe typical measures, normal development, and the available data on the effects of astigmatism-related deprivation and recovery. Thus, in the literature review that follows, I focus primarily on the clinical vision literature, as it is this body of research that has focused on deprivation in humans. However, since recent reports of recovery from the effects of deprivation have been noted in the literature on discrimination learning (e.g., Levi, Polat, and Hu, 1997, Polat and Ma-Naim, 2001), I will also include relevant information on discrimination learning for each of the visual perceptual functions in the summaries that follow. In the final discussion, I work towards bringing information from the clinical vision and experimental psychology literatures together, with the hope that integrating research and theory across the literatures will lead to a better understanding of human visual plasticity.

1.2.1 Recognition (Letter) Acuity

Recognition acuity is a measure of the perception of fine visual detail that is typically assessed with black letters or symbols on a white background. Recognition acuity measurements reflect the smallest stimulus size that the observer can both resolve and identify. An example of a letter acuity test is shown in Figure 3 (ETDRS Acuity Chart, Precision Vision, LaSalle, IL). Threshold letter acuity is typically reported in logMAR units (log value of the minimal angle of resolution), which is often transformed into more easily recognized and understood Snellen acuity values (e.g., 20/20).

Unlike measures of resolution acuity (e.g., grating acuity), recognition acuity measures represent the ability to identify the shape of the stimulus in addition to the ability to discriminate fine detail. Thus, recognition acuity thresholds represent stimulus sizes that are above detection thresholds, and are the minimum stimulus size at which the observer can also reliably identify the shape of the stimulus. While recognition acuity is often used in clinical evaluations of visual acuity, the theoretical interpretation of what this task measures is not clear (Riggs, 1965). For example, letter charts typically include several different letters, and it is not clear what aspect of the stimulus subjects use to make shape identification: for some letters, detection of a landmark feature may aid detection, and the size of that feature would of course influence identification at near threshold levels. In addition, while measures are surely influenced by resolution acuity thresholds, measures may also be influenced by limitations on shape discrimination. Despite this ambiguity in the interpretation of recognition acuity measures, these

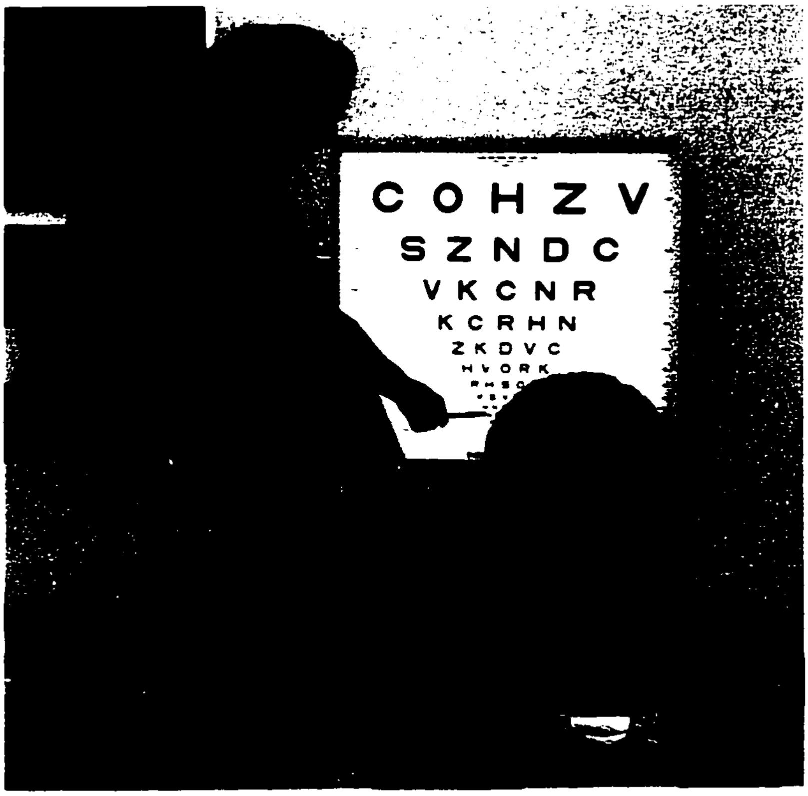


Figure 3. Letter acuity task.

measures do offer a practical measure of visual/perceptual performance that has relevance to everyday perceptual tasks.

As previously noted, different visual perceptual functions appear to have different developmental time courses, which could potentially make some visual functions more, or less, susceptible to the effects of deprivation and recovery from these effects during the 5- to 14-year-old age range. Therefore, before turning to research regarding the effects of astigmatism on letter acuity, I would like to make a brief note regarding what is know of the development of recognition acuity in normally developing children. Results of best-corrected recognition acuity for children in the grade-school age range measured with logMAR acuity charts have been provided by Dowdeswell, Slater, Broomhall, and Tripp (1995) who reported average acuity of 20/25 in a sample of 5.5- to 7-year-olds, and by Myers, Gidlewski, Quinn, Miller, and Dobson (1999) who reported average acuity of 20/20 in a sample of 10 year olds. The results of these studies, suggesting only a 1 line increase in recognition acuity between age 5-7 and 10, indicates that little development occurs in the grade-school age range in terms of recognition acuity, and adult levels appear to be reached at least by age 10.

Due to the orientation-dependent nature of deprivation associated with astigmatism, most studies of perception of fine visual detail in subjects with astigmatism have focused on grating acuity measurements for stimuli of different orientations, rather than recognition acuity measures of fine visual detail. However, three studies that have focused on members of the Tohono O'Odham Nation, a tribe in Arizona with a previously documented high prevalence of astigmatism, have reported recognition acuity measures in astigmatic subjects (Kershner and Brick, 1984, Dobson, Tyszko, Miller and Harvey, 1996, Dobson, Miller, Harvey, and Mohan, 2002). Kershner and Brick (1984) reported that in their sample of 4th and 5th grade Tohono O'Odham children, children with astigmatism (> 1.00 diopter) were more likely to have best-corrected visual acuity worse than 20/20. Dobson and her colleagues (1996) examined eye exam records for 100 consecutive patients (age 8 or older) seen at the Indian Health Services Hospital Optometry Clinic located on the Tohono O'Odham Reservation. The results indicated that in patients with little or no astigmatism (< 1D), 13% had below normal best-corrected letter acuity (i.e., acuity worse than 20/20 while wearing their appropriate eyeglass correction). This percentage increased in subjects with greater amounts of astigmatism from 30% in patients with low to moderate astigmatism (1 to < 3 D) to over 60% in patients with high astigmatism (4 D or more). More recently, Dobson and her colleagues (2002) reported on recognition acuity in 3- to 5-year old members of the Tohono O'Odham Nation. Rather than letter stimuli, this study used the Lea Symbols Acuity Chart (Precision Vision, LaSalle, IL), an eye chart that uses shapes (house, square, circle, heart) so that young children who are not adept at identifying letters can be tested. The results of the study indicated that for children with little or no astigmatism, average best-corrected acuity was approximately 20/40, but for children with high astigmatism, average acuity was approximately 20/50.

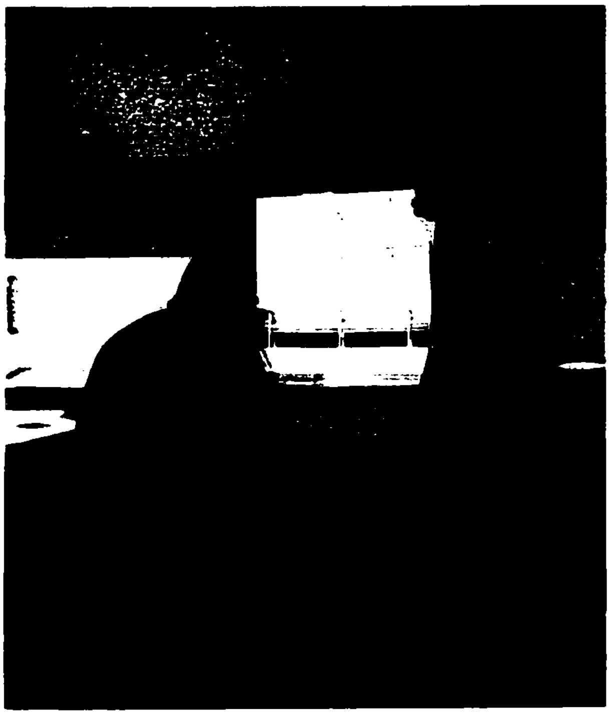
Overall, these data indicate that astigmatism is associated with recognition acuity deficits that persist even when appropriate eyeglass correction is worn, and support the idea that the presence of astigmatism during development results in deficits that are apparent as early as age 3 to 5 years. These data do not address recovery from astigmatism-related deprivation, however, and I am aware of no existing studies that address this question prospectively. However, a study recently completed (Miller, Dobson, Harvey, and Sherrill, 2000) did address recovery from effects of deprivation in the preschool subjects included in the report by Dobson et al. (2002), and the results of this study are forthcoming.

Finally, some recent studies have reported that discrimination learning in adult patients with deprivation-related perceptual deficits can result in improvements in recognition acuity. Levi, Polat, and Hu (1996) reported that for 2/6 amblyopic observers trained in a vernier discrimination task, the discrimination learning observed for vernier discriminations also resulted in improvements in letter acuity: one subject improved from 20/80 to 20/22, the other improved from 20/40 to 20/20. Polat, Ma-Naim, and Belkin (2001) reported that discrimination learning on contrast detection (across a range of stimulus orientations and spatial frequencies) resulted in an average improvement in letter acuity of 2.5 lines on the acuity chart in their sample of 44 subjects with amblyopia. Thus, while these studies did not include subjects with astigmatism-related amblyopia, they suggest that plasticity in recognition acuity can occur after discrimination learning for adult subjects with deprivation-related visual perceptual deficits.

1.2.2 Resolution (Grating) Acuity

Resolution acuity is a measure of the minimum distance between objects that an observer can detect (Riggs, 1965). Since the proposed study is aimed at evaluating changes in resolution acuity as a result of orientation dependent visual deprivation, grating acuity measures of resolution acuity for stimuli of different orientations are of particular interest. Grating acuity is measured as the size of the highest spatial frequency grating (black and white stripes) that can be resolved or discriminated (when they can not be resolved, the grating patch is perceived as a uniform gray patch). Spatial frequency is typically reported as the number of cycles (a cycle equals one black and one white stripe) per degree of visual angle (a degree of visual angle is roughly equal to the size of a dime held at arms length). The stimulus in Figure 4 is an example of a grating acuity test. On each trial, the observer views stimuli mounted behind three circular apertures. One circle contains a grating stimulus, the others contain gray patches. The stimuli are carefully constructed so that when the observer cannot resolve the grating, the grating stimulus appears the same as the gray patches. The observer's task is to indicate which of three circles contain a grating stimulus. Observers are shown cards with progressively finer stripes (higher spatial frequencies) until they reach a point at which the they can no longer perceive the grating, and perceive only a uniform gray shade in each of the circles.

Before discussing the influence of uncorrected astigmatism on development of grating acuity, I will first address studies on normal development of this visual function. A study conducted by Mayer and Dobson (1982) used an operant preferential looking technique to measure grating acuity in children from 5 months to 5 years of age, and compared development to measures in adult subjects. The results of the study indicated that by 4 years of age, grating acuity for children did not differ significantly from adult values. However, Ellemberg, Lewis, Liu, and Maurer (1999) compared grating acuity for children age 4- to 7- years-old to that of adults, and because the subjects were older and



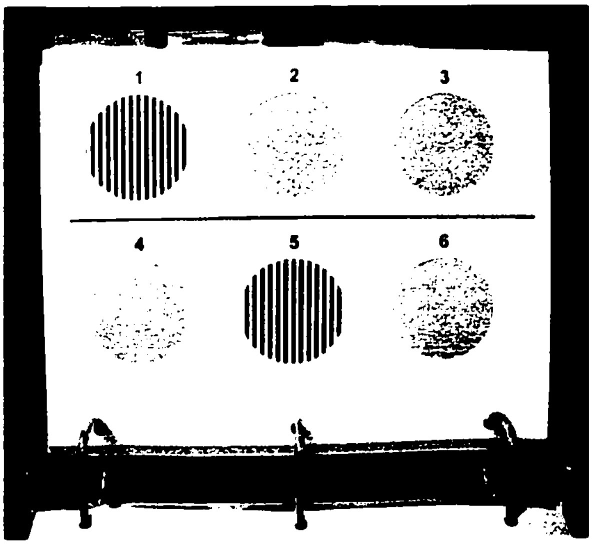


Figure 4. Grating acuity task. The upper photo shows a child being tested and the lower photo shows a close-up of the test stimuli.

were able to respond verbally, a method of limits procedure was used. The results indicated that grating acuity was adult-like by 6 years of age. The discrepancy in results between the two studies with regard to the age at which grating acuity reaches adult-like values (age 4 vs. age 6) is likely to be due to methodological differences between the studies, but from these studies we can conclude that normal development of resolution acuity as measured by grating stimuli is essentially complete by the time children reach 4-6 years of age.

What effects does uncorrected astigmatism have on development of grating acuity? A number of studies have provided evidence that the presence of astigmatism in infancy or early childhood can lead to reduced resolution acuity for stimuli of certain orientations even after the astigmatism is corrected (Mitchell, Freeman, Millodot, and Haegerstrom, 1973, Freeman, Mitchell, and Millodot, 1972, Gwiazda, Bauer, Thorn, and Held, 1986). Much of the research on the effects of astigmatism-related deprivation focus on the presence of this pattern of deficits, which is called *meridional amblyopia*, i.e., visual acuity deficits that are dependent on stimulus orientation.

Research suggests that, in order for astigmatism-related deficits to develop, astigmatism must be present during a specific period of visual development, i.e., a sensitive period. For example, it has been demonstrated that infants less that 1 year old who have astigmatism do not show evidence of meridional amblyopia (Teller, Allen, Regal, and Mayer, 1978, Gwiazda, Mohindra, Brill, and Held, 1985). However, several studies have reported the presence of meridional amblyopia in 3- to 5-year-old astigmatic children (Mohindra, Jacobson, and Held, 1983, Atkinson, Braddick, Bobier, Anker, Ehrlich, King, Watson, and Moore, 1996, Dobson, Miller, Harvey, and Mohan, 2002). These data suggest that that the sensitive period for susceptibility to the effects of astigmatism-related deprivation begins after age 1 year, and prior to age 3 to 5 years.

The age at which the sensitive period for susceptibility to the deprivation effects of astigmatism comes to an end is not known, I have been unable to find any specific reports of the relation between onset of astigmatism after age 7 and development visual perceptual deficits. Nonetheless, research suggests that other forms of visual deprivation (e.g., cataract, a clouding of the lens in the eye) that develop in late childhood and adulthood do not lead to the development of amblyopia (Kuman, Fedorov, and Novikova, 1984, Keech and Kutschke, 1995, Lewis, Maurer, and Brent, 1986).

Evidence regarding the extent of the plasticity associated with recovery from effects of astigmatism-related deprivation has been reported only in the form of retrospective studies of adults with astigmatism. In general, these studies indicate that if astigmatism is corrected with eyeglasses prior to age 7, astigmatic adults do not show evidence of meridional amblyopia, but if the astigmatism is corrected after age 7, the astigmatic adults may show evidence of meridional amblyopia. For example, Mitchell et al. (1973) reported meridional amblyopia in all of his adult astigmats who were corrected after age 6, and no meridional amblyopia in one astigmat corrected at age 3. Similarly, Cobb and MacDonald (1978) found that for their 12 astigmatic subjects, there appeared to be significant increase in meridional amblyopia for the subjects who received glasses after age 7, in comparison to the subjects who received glasses prior to age 7, who showed little evidence of meridional amblyopia. Mohindra, Jacobson, and Held (1983) reported that a 3-year old astigmatic child who showed evidence of meridional amblyopia upon initial testing showed no evidence of meridional amblyopia after 3 months of eyeglass wear. Thus, the limited evidence in the literature suggests that the sensitive period for successful reversal of meridional amblyopia through eyeglass treatment is prior to age 7 years.

In summary, the available research suggests that the sensitive period for susceptibility to the deprivation effects of astigmatism on resolution acuity begins towards the end of first year, and is likely to extend at least until the 7th year of life. The limited research on recovery from the effects of astigmatism-related deprivation suggests that the sensitive period for successful *treatment* of amblyopia is prior to age 7 years. However, these conclusions are based on retrospective studies of a small number of adult subjects (with the exception of the prospective report on one child subject reported by Mohindra, Jacobson, and Held (1983), as discussed above). While it is possible that this age would also correspond to the end of the sensitive period for the *development* of amblyopia due to deprivation, it is not necessarily so, and there is no existing evidence to indicate that astigmatism-related amblyopia is not likely to develop after age 7.

Are other forms of plasticity relevant to reversing the effects of astigmatism-related deprivation on grating acuity? Johnson and Leibowitz (1979) and Bennet and Westheimer (1991) looked at practice effects on grating acuity thresholds over thousand of trials conducted over a period of several days. The results of the two studies indicated that learning was not observed for centrally (foveally) presented stimuli, but was observed for stimuli presented peripherally. These data suggest that discrimination learning techniques may not be effective in improving grating acuity thresholds. However, since subjects included in these studies all had normal vision, it is possible that there was a ceiling effect, i.e., that subjects were already at or near their maximum level of central grating acuity performance, based on sensory limitations, prior to the start of the experiment. Subjects with reduced acuity due to deprivation may show improvements since they are clearly not, by definition, at the maximum acuity level relative to non-astigmatic subjects.

1.2.3 Vernier Acuity

Vernier acuity represents the finest amount of positional offset that can be detected. Figure 5 shows an example of a vernier acuity test. The observer's task is to report which line is offset, or "wiggly". Vernier acuity has been called a form of hyperacuity because the amount of offset that can be detected by a normal observer is approximately 7 times finer than their resolution acuity, and corresponds to a size that is finer than the size of retinal photoreceptors. Because of these features, it has been suggested that vernier acuity is a measure of positional acuity that is accomplished at the cortical level of the visual system. In addition, it is a more complex form of pattern processing than grating acuity and contrast sensitivity.

The developmental course of vernier acuity appears to be somewhat different than resolution acuity. Zanker and colleagues (1992) studied the development of vernier acuity from age 2 months to 8 years and reported that vernier acuity becomes adult-like by age 5 years. However, their results differ from other studies on several counts, including differences in vernier thresholds obtained at each age (their thresholds in

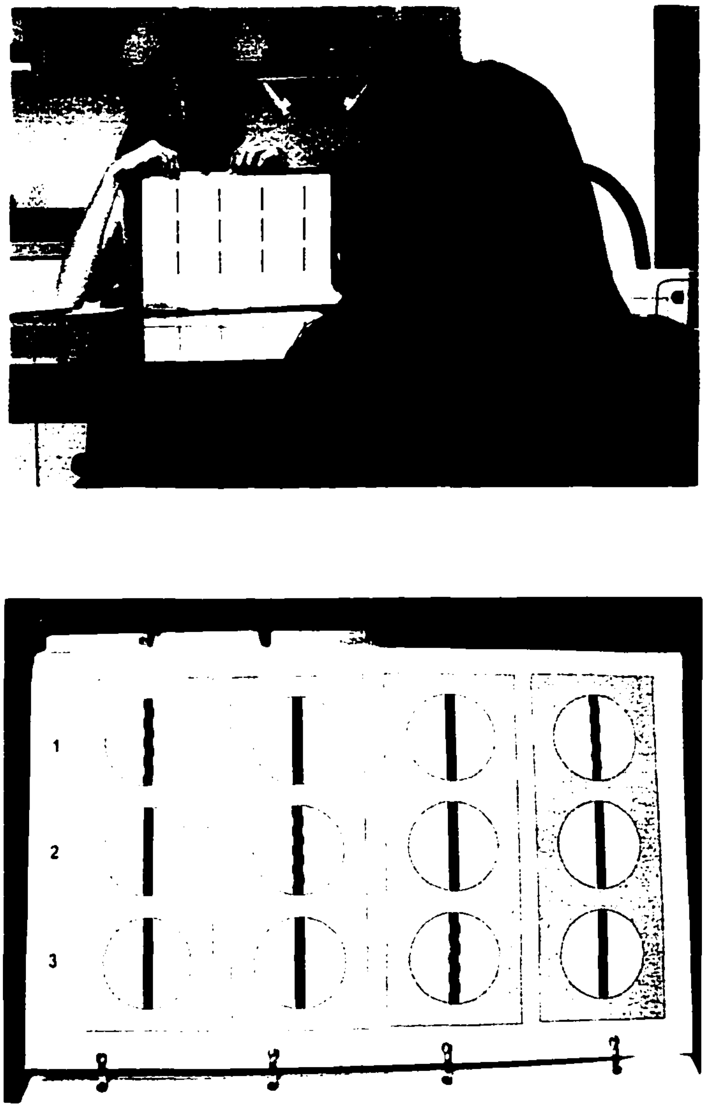


Figure 5. Vernier acuity task. The upper photo shows a child being tested and the lower photo shows a close-up of the test stimuli.

younger children were higher than previously reported), and on the age at which adult-like levels are reached, as most studies cite much later ages for full maturity of vernier acuity. Gwiazda (1987) reported that adult-like vernier acuity is not reached until approximately age 10, and Carkeet, Levi, and Manny (1997) reported that at age 6 years, vernier acuity is only half that of adults (they do not report the age at which adult values are obtained). In summary, these data suggest that vernier acuity development is more prolonged than grating acuity development, and may not reach adult levels until age 10 years.

A number of studies have provided evidence that the presence of astigmatism in infancy or early childhood can lead to orientation-dependent vernier acuity deficits that are present even after the astigmatism is corrected (Mitchell et al., 1973, Gwiazda et al., 1986). In addition, like resolution acuity, there is evidence that vernier acuity is associated with a sensitive period of development. Gwiazda and colleagues reported that reduced vernier acuity in non-astigmatic children was associated with amount of astigmatism present when the children were 6-12 months old, but not prior to that age. These data suggest that the period of susceptibility to vernier acuity deficits due to astigmatism begins at approximately 6 months of age. The end of the period of susceptibility for development of vernier acuity deficits is not clear. However, Mitchell et al. (1973) found orientation dependent vernier acuity deficits in one adult astigmat with meridional amblyopia who had worn eyeglasses since age 14, suggesting that the sensitive period ends prior to age 14.

As previously noted, the developmental course of resolution and vernier acuity greatly differ, with resolution acuity reaching adult-like values at approximately age five years, and vernier acuity reaching adult-like values at approximately age ten years. Therefore, it is possible that the sensitive period for vernier acuity might extend further than the sensitive period for resolution acuity. Levi and his colleagues have suggested that plasticity associated with vernier acuity may have a longer sensitive period because vernier acuity reflects perception of fine differences in spatial position. Changes that occur during growth (migration of retinal cells, changes in interpupillary distance, changes in the size of the eyes) would affect perception of spatial position, such as that which is measured in vernier acuity tasks. Therefore, it would be beneficial for the visual system to retain some level of plasticity for positional acuity at least until these growth related changes are complete (Levi and Carkeet, 1993).

While previous research has documented vernier acuity deficits in astigmatism-related amblyopia, it has not examined improvements in vernier acuity over time after removal of the deprivation. However, there are some reports regarding improvements in vernier acuity after removal of the deprivation conditions associated with other forms of amblyopia. Simmers and colleagues (Simmers, Gray, McGraw, and Will, 1999) reported improvement in vernier acuity in an adult strabismic amblyope and improvements in vernier acuity in children with various forms of amblyopia as a result of treatment (eyeglass wear and patching of the "good" eye, to force use of the amblyopic eye).

Is there further evidence in the literature for plasticity relevant to reversing the effects of visual deprivation on vernier acuity? Quite a bit of discrimination learning research indicates that vernier acuity can be improved with practice, and that improvement is specific to the trained stimulus orientation. In addition, these effects of practice have been documented in both normal and amblyopic subjects (Levi, Polat, and Hu, 1997). However, the amblyopic subjects in these experiments did not have astigmatism-related amblyopia. Regardless, if individuals with other forms of amblyopia show improvement, it is possible that individuals with meridional amblyopia will also show improvements in vernier acuity with practice.

1.2.4 Contrast Sensitivity

Contrast sensitivity represents the smallest difference in brightness between stimuli that can be detected, e.g., detection of shades of gray presented on a white background. Deficits in contrast sensitivity have important implications for visual perceptual functioning. For example, Skoczenski (2002) explains: " The capacity to see subtle brightness differences is critical for distinguishing the countless subtle shadings that define objects, and having poor contrast sensitivity is effectively like seeing one's surroundings through heavy fog: differences between light and dark are degraded and sharp edges are blurred".

Tests of contrast sensitivity typically use either letter stimuli or grating stimuli. Since the present study is aimed at determining the effects of orientation dependent visual deprivation and recovery, I will focus here on tests of contrast sensitivity that use grating stimuli. Figure 6 shows an example of a contrast sensitivity test (test revised from VCTS6500 Test, Vistech Consultants, LaSalle, IL). The observer's task is to report the orientation of the lines in each stimulus (horizontal, tilted left, or tilted right). Contrast

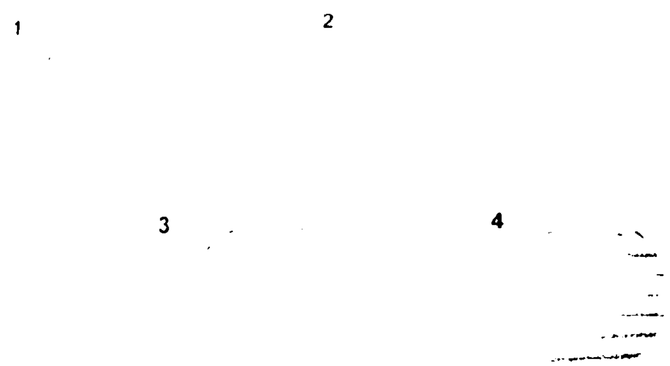


Figure 6. Contrast sensitivity task. The upper photo shows a child being tested and the lower photo shows a close-up of the test stimuli.

sensitivity for each spatial frequency is scored as the lowest contrast level at which the observer can correctly identify the orientation of the lines. Research indicates that contrast sensitivity in normal observers is best for mid-range spatial frequency stimuli, poorer for low spatial frequency stimuli (wide stripes), and worst for high spatial frequency stimuli (fine stripes). Thus, studies that employ contrast measures typically include measures over a range of spatial frequencies, and data are presented in the form of a contrast sensitivity function that relates the size of the stimulus to the threshold contrast level for detection.

It is important to note that contrast sensitivity and visual acuity, while measuring different functional aspects of vision, are not functionally independent of each other. For example, an individual with poor visual acuity is likely to demonstrate poor contrast sensitivity for high spatial frequency stimuli, particularly if the spatial frequency of the contrast stimuli is below or near visual acuity threshold. However, this individual may demonstrate more normal levels of contrast sensitivity when tested on low spatial frequency stimuli (e.g., wider stripes), particularly if the stimuli are significantly above visual acuity threshold. In summary, contrast sensitivity measures the smallest difference in contrast that can be detected, whereas visual acuity measures the smallest amount of high contrast detail that can be discriminated. While contrast sensitivity may be limited by visual acuity if high spatial frequency stimuli are used, measurements of contrast sensitivity for low spatial frequency stimuli may be less affected by visual acuity limitations.

Before discussion of the effects of uncorrected astigmatism on development of contrast sensitivity, I will first address normal development of contrast sensitivity. Ellemberg et al. (1999) compared contrast sensitivity for 4- to 7-year-olds to that of adult subjects. The results indicated that while there was still improvement from age 6 to age 7, at all spatial frequencies measured (0.33, 0.5, 1, 2, 10, and 20 cy/deg) contrast sensitivity was adult-like by age 7 years. Bradley and Freeman (1982) reported similar findings, concluding that contrast sensitivity across spatial frequencies reached adult levels by age 8 years. Three other studies reported different findings, however. Scharre, Cotter, Block, and Kelly (1990) reported that contrast sensitivity across spatial frequencies did not reach adult-like values by age 7 years, the oldest age included in their study. Adams and Courage (2002) reported that the age at which contrast sensitivity reached adult-like values was dependent on the spatial frequency of the stimuli, with contrast sensitivity for mid-range spatial frequency stimuli (4.8 cy/deg) reaching adult-like values by age 4 years, and contrast sensitivity for low spatial frequency stimuli (0.40 cy/deg) reaching adult-like values after age 7 years. Also, Gwiazda et al. (1997) reported that contrast sensitivity did not reach adult like levels by age 8 years, the oldest age group included in their study. It is likely that differences between studies are the result of stimulus differences and differences in testing procedures, but overall the data suggest that contrast sensitivity across spatial frequencies appears to be fully mature by about age 7 or perhaps shortly thereafter. This reflects slightly later attainment of maturity in comparison to grating acuity, and earlier maturity than vernier acuity.

A number of studies of astigmatic adults have provided evidence that the presence of astigmatism in infancy or early childhood can lead to reduced contrast sensitivity for stimuli of certain orientations, and that these deficits are present even after the astigmatism is corrected (Mitchell et al., 1973, Freeman, 1975, Freeman and Thibos, 1975). Freeman and Thibos (1975) found reduced contrast sensitivity across the range of spatial frequencies in meridional amblyopes. However, the age of subjects, and age of first eyeglass correction was not reported, providing no information relevant to the determination of a sensitive period for the effects of meridional deprivation on contrast sensitivity. Mitchell and Wilkinson (1974) reported reduced contrast sensitivity across a range of spatial frequencies in two adult meridional amblyopes who received optical correction at the age of 10. These findings suggest that the blur associated with astigmatism affects contrast sensitivity across stimuli of various spatial frequencies, and suggest that the end of the sensitive period for susceptibility to the deprivation effects of astigmatism on contrast sensitivity is prior to age 10.

The literature has documented contrast sensitivity deficits in meridional amblyopes, but has not examined improvements in contrast sensitivity over time after correction of astigmatism, i.e., recovery from the effects of astigmatism-related amblyopia. However, as previously noted, Mitchell and Wilkinson (1974) reported reduced contrast sensitivity in astigmats who received their first correction for astigmatism at age 10, suggesting that correction of the deprivation effects of astigmatism must occur prior to age 10 to reverse or avert the development of contrast sensitivity deficits.

Finally, it is important to note that there are some reports in the literature of improvement in contrast sensitivity with practice in adult subjects. DeValois (1977) reported improvements in contrast sensitivity for two subjects who were repeatedly tested in psychophysical contrast sensitivity studies over time, in which their contrast sensitivity thresholds were determined repeatedly for stimuli of various spatial frequencies. Recently, Furmanski and Engel (2002) reported discrimination learning for contrast sensitivity for obliquely oriented grating stimuli, and Sowden, Rose and Davies (2002) reported spatial frequency specific learning for contrast sensitivity using grating stimuli.

1.2.5 Stereoacuity

Depth perception in humans utilizes both monocular and binocular cues. In measures of stereoacuity, we are interested in measuring the extent to which we can utilize binocular cues in perception of depth. More specifically, stereoacuity is a measure of the extent to which our visual system can utilize the difference in visual images obtained through our eyes that arises due to the differences in spatial location of the two eyes (i.e., slightly different viewpoints), and the extent to which this information is utilized to give rise to the perception of depth. Measures of stereoacuity are threshold measures of the finest interocular difference between images that we can detect, and which can result in the perception of depth.

Since monocular cues to depth are very effective, measures of stereoacuity typically control for monocular cues to depth. The primary technique for eliminating monocular cues is through the use of random dot stereograms (Julesz, 1971). Random dot stereograms are generated by creating two identical patches of randomly arranged dots. One of the images is then altered by selecting a section of dots (e.g., a central square) and shifting them horizontally (i.e., to the right in one image, and to the left in the other). When the different images are viewed by the two eyes, the difference in location of the central square across stimuli mimics the interocular difference when viewing real-world objects, and the square appears to float in front of or behind the patch of dots. In the literature review and the study that follows, random dot stereograms were used to assess stereoacuity. Figure 7 illustrates a child being tested with a random dot test of stereoacuity (Randot Preschool Stereoacuity Test, Stereo Optical Co, Chicago, IL).

Interpretation of data regarding plasticity in stereoacuity in the present study is complicated because there are potentially different sources of changes in visual experience that could reduce best-corrected stereoacuity. First, it is possible that deprivation due to astigmatism may result in deficits in stereoacuity, as it seems to result in deficits for other fine perceptual functions. In addition, it is also possible that wearing cylinder lenses to correct for astigmatism could reduce stereoacuity due to interocular differences in the spatial distortion caused by the cylinder lenses, as I will discuss in more detail in the next section. Thus, if astigmats show reduced stereoacuity when glasses are first worn, it is not clear if the deficits are due to the deprivation effects of the previously uncorrected astigmatism, or if the deficits are due to spatial distortion induced by the corrective lenses. Of course, if no deficits in stereoacuity are observed we have evidence against both of these hypotheses. In what follows, I summarize the available literature on the relation between astigmatism-related deprivation and stereoacuity, which is very limited. For this reason, even though stereoacuity data obtained in the present study are

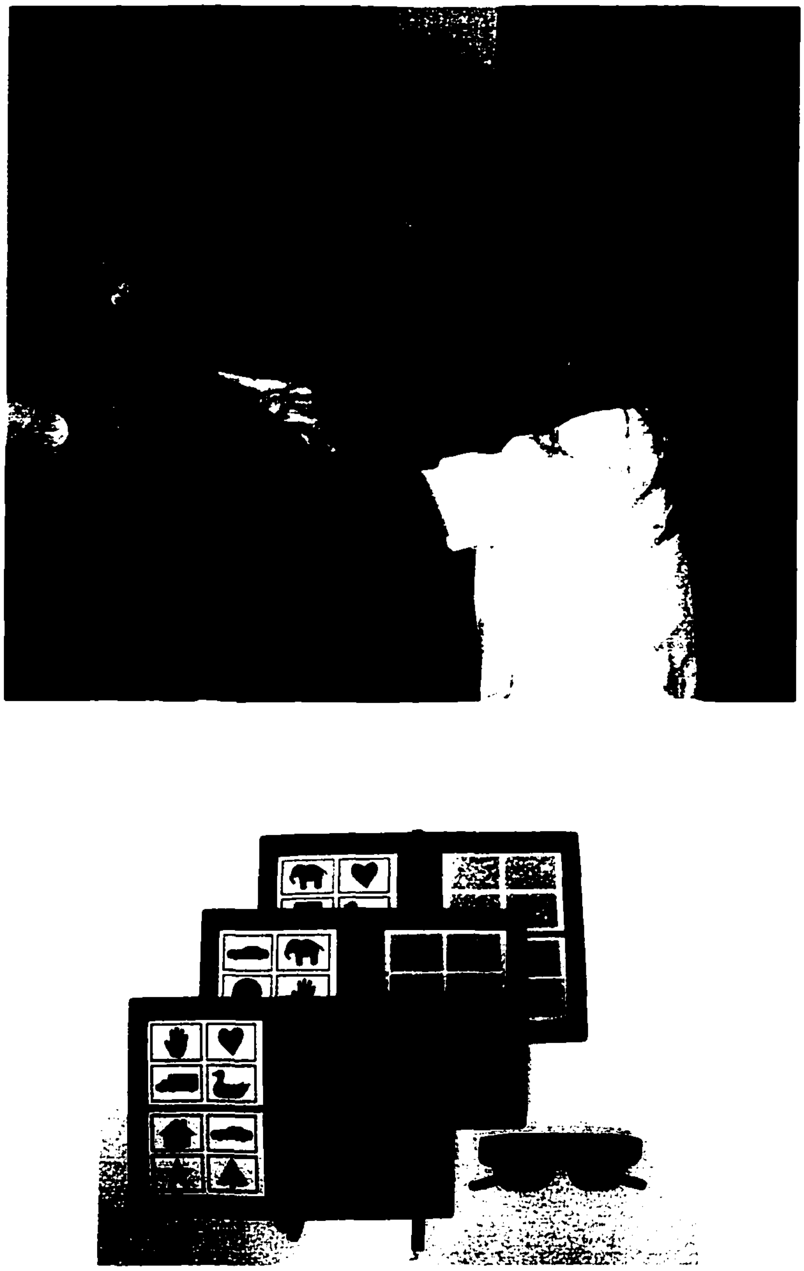


Figure 7. Stereoacuity task. The upper photo shows a child being tested and the lower photo shows a close-up of the test stimuli.

confounded, I believe it will add significantly to the currently available data on the effects of astigmatism-related deprivation, in addition to the literature on adaptation to spatial distortion, as summarized in the next section.

Estimates of stereoacuity in infants and children have indicated that by age 5, stereoacuity development is essentially complete. Ciner, Schanel-Klitsch, Herzberg (1996) measured stereoacuity using random dot stimuli in a sample of children ranging from age 6 months to 5 years. The results indicated that by age 2.5 to 5 years mean stereoacuity was approximately 50 sec arc, approaching adult levels of 20 seconds of arc. The study also included two children who were between 5 and 5.5 years old, and stereo-acuity in these children was 20 and 40 sec arc, respectively, suggesting that by age 5, stereoacuity can reach full maturity. These results are in agreement with those reported by Fox, Patterson, and Francis (1986), who measured stereoacuity in 3- to 5-year-olds using the "standard three-rod test" (not a random dot test of stereoacuity), and found that while there were significant differences in stereoacuity between the adults and children, median stereoacuity for children approached adult levels at this age.

Does astigmatism-related deprivation result in reduced stereoacuity, even after the deprivation is alleviated? A recent study found reduced stereoacuity in the presence of simulated (lens induced) astigmatism (Chen, Kaye, McCloskey, Mfazo, Rubin, and Harris, 2002). While this study confirms that the uncorrected optical deprivation induced by astigmatism is sufficient to reduce stereoacuity, it does not address plasticity. That is, it does not tell us if individuals with high astigmatism show reduced stereoacuity when the astigmatism is corrected. Only one study that I am aware of has measured the effects of astigmatism-related deprivation on stereoacuity. Mitchell et al. (1973) compared stereoacuity for horizontal vs. vertical stimuli in one adult astigmat who had meridional amblyopia, and reported poorer stereoacuity for horizontal stimuli, which was the stimulus orientation for which the subject had experienced the greatest astigmatism-related deprivation. While it is likely that this subject had reduce stereoacuity compared to non-astigmatic subjects, absolute stereoacuity thresholds in comparison to non-astigmatic subjects were not reported in the study (i.e., they reported comparisons between stereoacuity thresholds for horizontal and vertical stimuli in units of standard deviations of repeated measures).

While there is very limited research on the relation between stereoacuity and astigmatism-related deprivation, research on children with strabismus (poor ocular alignment), anisometropia (difference in quality of visual inputs between eyes), and cataract (clouding of the lens that restricts visual input) has provided important information on the susceptibility of depth perception (stereopsis) the effects of visual deprivation. For example, research has indicated poor spatial correspondence between eyes can result in a lack of stereopsis in children with strabismus, and that stereo deficits often persist *even after the eyes have been aligned.* Studies indicate that from age 1 to 3 years of age, children with strabismus are at risk for loss of stereopsis (Banks, Aslin, and Letson, 1975). These findings suggest that there is a critical period for susceptibility to the influence of poor ocular alignment on the disruption of stereopsis, and that this sensitive period extends from age 1 to age 3 years. However, some studies have demonstrated that older children and even adults with deprivation-related stereo deficits can show improvements in stereoacuity (Brown, Archer, and Del Monte, 1999, Mintz-Hittner and Fernandez, 2000, Morris et al., 1993). However, it is not clear to what extent these data apply to the effects of astigmatism-related deprivation and recovery from these possible effects.

Finally, evidence of improvement in stereopsis in normal adults has been reported in research that has demonstrated improvements in the ability to fuse random dot stereograms (e.g., Ramachandran and Braddick, 1973, Ramachandran, 1976). However, some have suggested that improvements may be due to attentional factors, rather than learning associated with visual processing (Sowden, Davies, and Rose, 1996). Thus, the literature does not provide any clear indication that practice can or cannot influence achievement of stereopsis.

1.2.6 Summary

In summary, the effects of astigmatism-related deprivation have been reported to some extent for each of the visual perceptual functions to be studied here: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity. However, prospective studies on plasticity associated with recovery from the effects of astigmatism-related deprivation through eyeglass wear (restoration of clear images to the retina) have not been reported prior to the present study. The results of this study will make a significant contribution to the literature by providing important evidence regarding plasticity associated with recovery from the effects of astigmatism-related deprivation in children in the 5- to 14-year-old age range. In addition, analyses of baseline data will also add significantly to the literature by providing data from a large sample of astigmats on the patterns of perceptual deficits present in children who experienced astigmatism-related deprivation.

Previous studies of normal development indicate that there are differences in the age at which visual/perceptual functions reach full maturity: While there is some disagreement across studies, the data in general indicate that maturity is reached by age 5 years for stereoacuity, by age 4 to 6 years for grating acuity, by age 7 for contrast sensitivity, at least by age 10 for letter acuity, and approximately age 10 for vernier acuity. With regard to the age range of subjects in present study, the literature suggests that development of some functions is essentially complete in our sample of 5- to 14-year-olds (grating acuity, stereoacuity), while some development continues within this age range for others functions (letter acuity, vernier acuity, and contrast sensitivity). Analysis of control group data from non-astigmatic subjects will add to the literature on normal development of visual perceptual functions: it will provide a within-subjects comparison of visual functions across a wide age range of children with normal visual development.

1.3 The Effects of Cylinder Lenses on Depth Perception

As noted in the previous section, measurements of stereoacuity in the present study are confounded, i.e., any deficits observed could be attributed to either astigmatism-related deprivation or to the distortion induced by the cylinder lenses that correct the astigmatism. In the previous section, I summarized the existing data on the relation between astigmatism-related deprivation and stereoacuity. In this section, I summarize previous work regarding the effects of cylinder lenses on perception of depth, and provide a summary of the existing evidence for adaptation to such effects.

Viewing the world through a cylinder lens, i.e., a lens that has unequal curvature across meridia causes two changes in perception. First, there is change orientation dependent focus or resolution acuity as described in the previous section. Second, there is a spatial distortion associated with the differential refraction of light across orientations as it enters the eye. Examples of the types of spatial distortions observed are outlined by Guyton (1977). In general, the lens distorts the stimulus by disrupting the size ratios across orientations. Thus, a circle when viewed through a cylinder lens will look oval. The amount of distortion observed is determined by two factors, the power of the lens (i.e., the difference in curvature across orientations: the greater the difference in curvature, the greater the distortion) and the distance of the lens from the pupil (the larger the distance, the greater the distortion).

The spatial distortion is reduced as the cylinder lens is placed closer to the eye, and is minimal when the unequal curvature is located in the actual structure of the cornea or lens of the eye. For example, Guyton (1977) reports only 0.33% distortion per diopter of astigmatism, whereas cylinder lenses result in approximately 1% distortion per diopter of cylinder in the lens. Thus, astigmatism in the eye does not cause the same perceived spatial distortion as cylinder lenses placed in front of the eye: Astigmatic individuals who are not wearing eyeglass correction do not experience the type of spatial distortion induced by cylinder lenses.

An example of the disruption in spatial correspondence that is likely to occur with the prescription of cylinder lenses for astigmatism is illustrated in Figure 8. These disruptions can occur as a result of differences in amount of cylinder in the lenses and/or differences in the axis of the cylinder lenses between eyes. For example, if one eye views the stimulus shown in Figure 8a through an cylinder lens at an orientation that that results in the distortion illustrated in 8b and the other eye views through a stronger cylinder lens that results in the distortion in Figure 8c, you can see that if you overlap these two stimuli, as demonstrated in 8d, the inter-ocular spatial correspondence between the two images is disrupted. In this example, there is no difference in the orientation (axis) of cylinder lenses in front of each eye, but there is a difference in the amount of distortion between eyes. Differences in the orientation of astigmatism between eyes will also result in disruption of spatial correspondence between eyes. If one eye views through a lens oriented such that it results in the distortion illustrated in Figure 8e, and the other eye views through a lens that results in the distortion illustrated in Figure 8f, we can see as illustrated in Figure 8g that there will be disruption in spatial correspondence between eyes. In this example the power of the cylinder lens is the same across eyes, only the orientation of the cylinder lens differs.

Previous studies of the binocular perceptual effects associated with cylinder lenses are based on differential spatial distortion between eyes. Much of the research in this are has been conducted using a special type of lens called a meridional size lens (MSL). This type of lens has been used, rather than a simple lens with cylinder in it, because these studies used non-astigmatic observers, and putting cylinder lenses in front

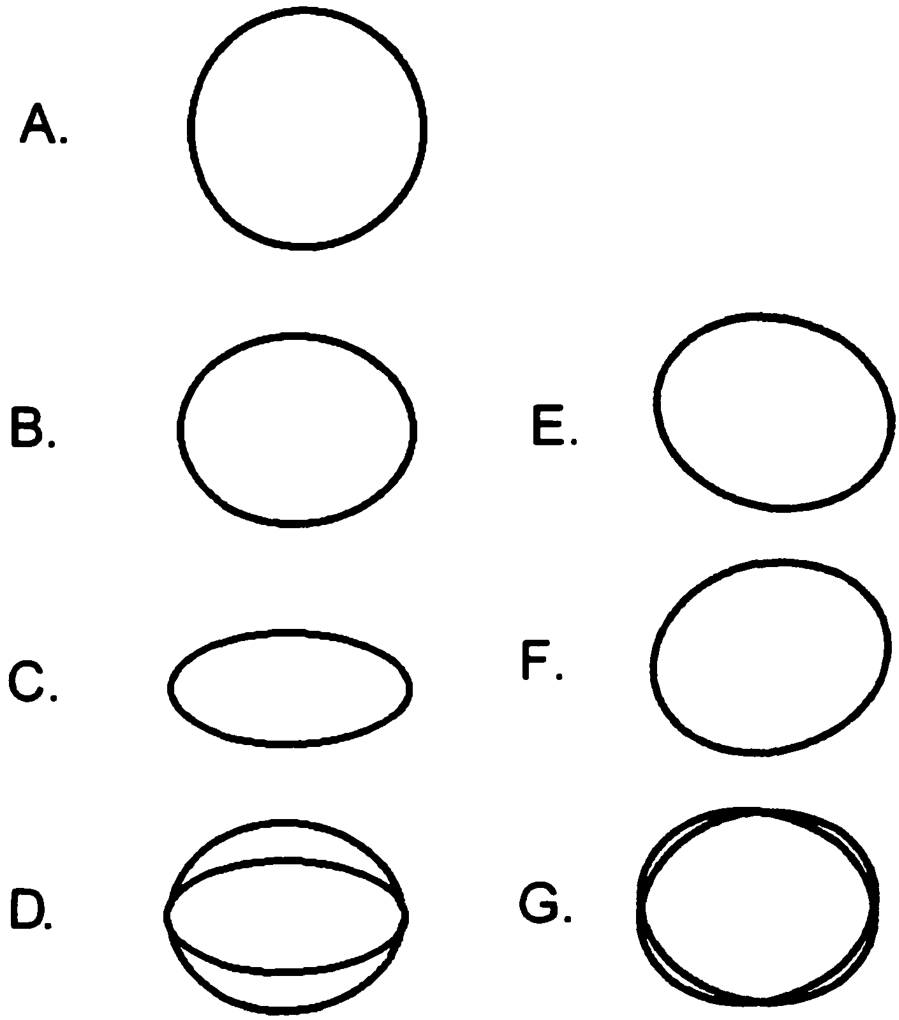


Figure 8. Meridional size distortion demonstration. Figure A represents the standard stimulus. Figures B and C represent different amounts of meridional distortion, and figure D represents spatial overlap of distortions illustrated in B and C. Figures E and F represent different axes of meridional distortion, and G represents spatial overlap of distortions illustrated in E and F.

of a non-astigmatic eye will result in spatial distortion *and* defocus for stimuli of certain orientations. MSLs provide meridional size distortion *without* orientation-dependent defocus for non-astigmatic observers. Wearing a MSL in front of one eye disrupts the spatial mapping between the eyes and disrupts interocular spatial correspondence. The result is the perception of slant in physically flat surfaces, an effect that is most noticeable in the absence of monocular depth cues (See Ames, 1946, for a detailed illustration and explanation of these perceptual effects).

Several studies have examined adaptation to the depth distortions induced by MSLs (e.g., Burrian, 1943, Morrison, 1972, Epstein and colleagues, 1970, 1971, 1972). The results of these studies are quite consistent. When subjects wear MSLs over one eye (axis 90 degrees, in which the size of the horizontal axis is distorted) with the other eye unoccluded, they initially experience distortions in depth perception, as described by Ames (1946). After several days of wear, subjects typically report extensive reduction in perceived distortion in environments in which monocular depth cues are abundant. However, when measurements of depth perception are obtained under conditions in which monocular cues are essentially eliminated, the distortion is still present. These data suggest that to some degree adaptation to the distortion might consist of suppression of stereoscopic depth information, and an increased focus on monocular cues. However, the data from these studies also indicated that the amount of distortion measured under conditions that eliminate monocular depth cues decreases with the length of wear, and that a negative aftereffect in depth judgments is observed after the lenses are removed, although full adaptation in the absence of monocular cues has not been reported.

Morrison (1972) reports a case of a patient who had worn eyeglasses since childhood, and then began wearing contact lenses as an adult. As previously noted, the closer the lens is in relation to the eye, the less distortion occurs. Therefore, based on the optical principles applied to eyeglasses and contact lens, the eyeglasses should have provided the patient with a distorted image, whereas the contact lens should not. However, this patient reported typical symptoms of depth distortion *when wearing the contact lenses*. Morrison suggests that the patient had adapted to the distortion produced by the eyeglasses, such that when the eyeglasses were removed, the patient experienced an aftereffect. However, the extent of the aftereffect (relative to the distortion of the eyeglass lenses) was not reported. It is possible that with prolonged wear, perhaps during a sensitive period of development, full adaptation might occur.

Typically, studies have examined binocular effects in individuals wearing distorting lenses in front of one eye, so the relative distortion between eyes has not been studied. In addition, effects have been measured based on gross measures of stereo vision, rather than fine measures, such as stereoacuity. No data exist to indicate how much of a difference in power of cylinder lenses between eyes and how much of a difference in axis of cylinder lenses between eyes is necessary in order to disrupt stereoacuity. However, it is possible that individuals who are given lenses for the correction of astigmatism will experience disruption in stereoacuity (minimum amount of binocular disparity that results in percept of depth), and/or a distorted sense of depth, but only if they have differences in cylinder power and/or axis between eyes.

1.4 The Effects of Cylinder Lenses on Form Perception

In the previous section, I reported that viewing through an astigmatic lens produces orientation dependent size distortion and cited evidence that the effects of this distortion may influence stereoacuity if there are differences in the distortion between eyes. In this section, however, I focus specifically on the distortions of form perception, and literature on plasticity as it relates to adaptation to these distortions in form perception. Examples of these distortions are provided in Figure 8. Do perceptual changes occur over time as a result of the introduction of this form of altered visual experience?

While adaptation to this type of distortion induced by cylinder lenses in clinical practice has not been directly measured in patients, the distortion induced by such lenses is common knowledge among clinicians. Guyton (1977) documents several observations that are apparently well known among clinicians. For example, he suggests that the ability to adapt to cylinder lenses varies across age: "It is a common clinical observation that children adapt readily to induced distortion from astigmatic spectacle corrections." More specifically, he notes that ".... physiological adaptation is age dependent.... The ability is well developed in children and decreases rapidly with advancing age". In the absence of empirical data regarding developmental effects of form adaptation, these clinical observations represent the only indication available, to my knowledge, that there are developmental differences in form adaptation, and perhaps a sensitive period for form adaptation.

Studies of adaptation to the types of binocular and monocular distortions that occur with cylinder lenses have been conducted using meridional size lenses (MSL), and have been reported in the experimental psychology literature. Mack and Quartin (1974, cited in Welch, 1978) conducted a study in which observers wore a MSL over one eye, with the other eye occluded. The MSLs were worn in an orientation that caused monocular distortion (elongation) in the horizontal axis (10% and 25% magnification was used). Subjects wore the lens for 1-8 hours, and adaptation was determined by measuring the extent of the aftereffect. That is, subjects adjusted a rectangle until it appeared to them to be a square. Judgments were made first when they initially put on the lens, and again after they had taken off the lens after 1-8 hours of wear, during which they walked through corridors. Aftereffects varied from 15% to 49% of the initial distortion, depending on the degree of magnification and the length of wear. The results of this study suggest that at least some degree of adaptation in form perception can occur with short-term wear of MSLs.

In the present study, I will determine if 5- to 14-year-old children adapt to the monocular distortions induced by cylinder lenses prescribed for correction of astigmatism. Studies of meridional size lenses conducted with adult subjects demonstrated partial adaptation to the size distortion. It is not known if longer term wear might result in greater, or perhaps full adaptation to the lenses. However, in the study by Mack and Quartin (1974, cited in Welch, 1978), there was no significant difference between the amount of adaptation observed after 1 hour and the amount of adaptation observed after 8 hours of exposure to the distortion, suggesting that it is unlikely that longer wear would produce significant increases in percent adaptation. However, clinical observations suggest that children may demonstrate greater adaptation to the lenses than adults (Guyton, 1977). These observations are consistent with the idea put forth by Pettigrew (1978) (specifically with regard to adaptation to changes in depth disparity relations that occur through growth) that there is perhaps a sensitive for perceptual adaptation. Thus, if there is a sensitive period for adaptation, the young subjects in the present study may show more adaptation than has been previously reported for adult subjects.

1.5 Summary

To sum up the previous sections, there is evidence in the literature that astigmatism-related deprivation results in reduced visual perceptual abilities in terms of recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity. However, the data on extent of the plasticity related to recovery from the effects of this form of deprivation are very limited. In addition, there is evidence of partial adaptation to the type of form distortion induced by the lenses that correct for the deprivation effects of astigmatism, but adaptation to this type of distortion has not been previously reported in children. In the present study, I will examine plasticity for each of these measures of visual perception in 5- to 14-year-old children: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, stereoacuity, and form perception. Subjects will be drawn from a sample that spans the upper age limit (age 5 to 14 years) of the hypothesized end of the sensitivity period (approximately age seven) for development of many of these aspects of visual perception. The primary goal of the present study is to work towards filling the gap in the clinical vision literature on plasticity associated with recovery from the effects of astigmatism-related deprivation, and to work towards filling the gap in the experimental psychology literature on plasticity associated with perceptual adaptation in children.

Another form of visual plasticity, discrimination learning, is not included in the experimental design. However, as I have noted in the introductory sections, and as I will further explore in the final discussion, the exchange of ideas and collaboration between clinical vision research on deprivation and experimental psychology research on perceptual adaptation and discrimination learning may provide a particularly valuable path towards better understanding of human visual plasticity, and may result in the development of important new treatment options for individuals with visual/perceptual deficits related to deprivation.

2. A STUDY OF VISUAL DEVELOPMENT AND PLASTICITY

2.1 Introduction

The primary goal of the present study is to examine the extent to which 5- to 14-year-old children demonstrate plasticity with respect to recovery from the effects of astigmatism-related deprivation and adaptation to form distortion. Secondary goals of the present study include evaluation of perceptual development in children between the ages of 5 and 14 years and determination of the effects of high astigmatism on visual perceptual development.

This study is a within-subjects comparison of the limits plasticity associated with six visual/perceptual functions: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, stereoacuity, and monocular form perception. The subjects in the experimental group are children with high astigmatism, a condition of the eye that induced a form of visual deprivation. The experimental manipulation will consist of altering visual experience through eyeglass correction of astigmatism. This manipulation results in two changes in sensory input: alleviation of the deprivation effects of astigmatism by allowing the eye to focus clear images on the retina, and meridional size distortion. Thus, the same method (same pair of eyeglasses) alters visual experience for each of these different aspects of vision allows for comparisons in plasticity observed based on equivalent amounts of visual perceptual experience.

Analyses will address the following research questions:

1. For 5- to 14-year-old children, is there evidence of plasticity associated with recovery from astigmatism-related visual deficits within a 1 month or 1 year period of good/clear visual experience, and is there plasticity associated with adaptation to form distortion within a 1 month period?
2. What do baseline data tell us about normal perceptual development in non-astigmatic children within the 5- to 14-year-old age range, and the effects of astigmatism-related deprivation on perceptual development?
    a. Is there evidence of development of recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity in normal (non-astigmatic) children within the 5- to 14-year-old age range?
    b. What patterns of visual perceptual deficits are apparent in children who experienced astigmatism-related visual deprivation and is there measurable form distortion when the children are first given their eyeglasses?

2.2 Study Design and Methods

The present study was conducted on the Tohono O'Odham reservation, located in southern Arizona. As previously mentioned, this population is of particular interest for the study of the effects of astigmatism on visual development because previous research has indicated that Tohono O'Odham children and adults have an unusually high prevalence of astigmatism. For example, the prevalence of high astigmatism in urban populations of grade-school children has been reported as 3-7% (Hirsch, 1963, Woodruff, 1986, Coleman, 1970), whereas the prevalence of high astigmatism in Tohono O'Odham children is approximately 33% (Dobson, Miller, and Harvey, 1999, Miller, Dobson, Harvey, and Sherrill, 2001). Furthermore, previous work with Tohono O'Odham children has indicated that many are at risk for the development of visual deficits due to uncorrected astigmatism: few grade school children are currently wearing glasses for astigmatism, and many report never having worn glasses (Dobson, Miller, Harvey, and Sherrill, 1999). Thus, this population was chosen because it is likely that there is a high prevalence of astigmatism-related visual deficits among Tohono O'Odham children, and pilot data have supported this prediction.

Data collection was performed in five parts: (1) baseline eye exam and determination of appropriate eyeglass prescription, (2) eyeglass intervention and baseline vision testing, (3) 1 month follow-up vision testing, (4) 1 year follow-up eye examination and eyeglass prescription update, and (4) 1 year follow-up vision testing.

At the baseline eye examination, each child received a complete eye examination including cycloplegic refraction, conducted by a pediatric ophthalmologist to determine the if child's eyes were developing normally, and to determine the child's best eyeglass correction/prescription. Only children who had >/= 2.00 diopters (D) of astigmatism in either eye, or had uncorrected vision worse than 20/20 and met the following criteria were prescribed eyeglasses:

Myopia >/= 0.75 D in either meridian

Hyperopia >/= 2.50 D in either meridian

Astigmatism >/= 1.00 D in either eye

Anisometropia >/= 1.50 D spherical equivalent

The children were encouraged to wear eyeglasses on an ongoing basis upon dispensing of the eyeglasses, which occurred at the baseline vision testing session.

Although not all children met the above criteria and were therefore not prescribed glasses for continual use, all children wore glasses during the vision testing sessions. This was done so that measurements of all children would reflect their best possible vision, and also to reduce tester bias, i.e., to mask the testers as to which children had high astigmatism. For children who had minimal prescriptions and did not meet the above prescribing criteria, a set of "stock" eyeglasses was used. Thus, if a child did not require a prescription for long-term-use, the child's prescription was matched to the stock pair of eyeglasses that were closest to their prescription such that both right and left lenses were within 0.50 vector dioptric difference from the child's refractive error (calculation method described by Long, 1976, and modified by Harris, 1990). If a pair of stock glasses did not meet these criteria, a new pair was ordered for the child to wear during vision testing.

The baseline vision testing session was conducted on a separate day approximately 2-3 weeks after the eye exam. A team of several trained testers conducted vision testing. Vision tests included distance letter acuity, horizontal and vertical grating acuity, horizontal and vertical vernier acuity, horizontal and vertical contrast sensitivity for low, middle, and high spatial frequency stimuli, stereoacuity, and monocular form perception. Details of the test stimuli and procedures are provided in the next section.

At the end of the baseline vision testing session, children who were prescribed eyeglasses and children in the control group with significant myopia (nearsightedness), hyperopia (farsightedness), or anisometropia (difference in refractive error between eyes) were given their eyeglasses to wear for a 1 month period. A project staff member visited the school weekly to encourage the children to wear the eyeglasses, to adjust or repair the eyeglasses when necessary, and to dispense a new pair if the eyeglasses become lost or broken. In order to maximize glasses wear, the staff member carried a spare pair of glasses for each child who required them, so that children were not without glasses for any length of time if they lost or broke them. A replacement pair of eyeglasses was immediately ordered once the spare was dispensed, and the number of eyeglass replacements per child was unlimited.

Follow-up vision testing was conducted at least 1 month after the glasses were dispensed, and after approximately 1 year. Prior to the 1 year follow-up vision testing session, each child received another eye examination, and eyeglass prescriptions were updated. Each child wore her or his updated eyeglass prescription for the 1 year vision testing session. The follow-up vision testing sessions were identical to the baseline vision testing session.

2.2.1 Subjects

Subjects were children who attended the San Xavier Mission School, an elementary school on the Tohono O'Odham Reservation, during the 2000/01 school year or the 2001/02 school year, and whose parent or guardian provided written consent for participation. We attempted to recruit all children in grades K through 8 for participation in 2000/01. In addition, in 2001/02 we attempted to recruit all children who were newly enrolled in the school (including the entire kindergarten class) for participation. The majority of children were Native American and were members of the Tohono O'Odham Tribe.

2.2.2 Stimuli and Testing Methods

Due to time constraints and limits on the attention span of some children tested (particularly the very young children), testing was conducted for the right eye only (i.e., the left eye was occluded with an eye patch), with the exception of stereoacuity.

Test order was randomized across subjects for measures of letter acuity, grating acuity, vernier acuity, contrast sensitivity, and stereoacuity. Each subject was randomly assigned a test order at the baseline vision testing session (one of the 120 possible test orders that can be generated using 5 tests), and each subject was tested in the same order at baseline and follow-up. This design was implemented to reduce the chance that differences from baseline to follow-up within a measure of vision might be obtained due change in test order from baseline to 1 month and 1 year. Subjects participated in the form perception measurements when they were waiting their turn for other tests.

Recognition (Letter) Acuity: Letter acuity was tested at a distance of 4 meters using the ETDRS log MAR letter acuity chart (Precision Vision, Inc.). An illustration of a child being tested is provided in Figure 3. Each line on the chart contains five letters. Beginning with the top line (20/200), the subject was asked to identify all five letters on each line of the chart, until he or she could no longer identify any of the five letters on a line. Visual acuity was scored as the smallest line on which the child could correctly identify at least three of five letters. If children were unsure of their letters, they were given a lap card that contained all of the letters that appear on the chart, and were asked to respond by matching the letters on the chart to the letters on the card.

Resolution (Grating) Acuity: Grating acuity stimuli were constructed using unmounted Teller Acuity Cards (Vistech Consultants, Inc., LaSalle, IL), a commercially available test of grating acuity that was designed for clinical testing of visual acuity in infants and individuals who are not able to identify letters using a traditional visual acuity letter chart. The Teller Acuity Card stimuli could not be used as constructed because they include only vertical line stimuli.

The Teller Acuity Cards consist of a 12.5 by 12.5 cm patch of grating surrounded by luminance-matched gray. The cards are constructed so that when an individual is unable to perceive the stripes, the grating patch appears a uniform gray that matches the rest of the card. Several sets of cards were purchased, and new stimuli were constructed from the cards by mounting the stripes and matching gray area from the same card behind circular apertures to produce 3-alternative-forced-choice (3AFC) task for horizontal, vertical and oblique grating stimuli. An illustration of a child being tested and the test stimuli are provided in Figure 4. Subjects' task was to identify which one of the circles (number 1, 2, or 3) contained the stripes. On an individual trial, subjects had a 1/3 chance of correctly guessing the correct location of the stripes. To further reduce the chance of correct guessing, stimuli for four 3AFC trials were constructed for each grating spatial frequency and line orientation, and subjects were required to correctly identify the location of the stripes on at least three out of four trials. Using this method, the chance of correctly guessing the location the stripes on three of four trials was 11%.

The stimuli were assembled and organized into a test book. The book includes stripe widths ranging from 38 cycles/cm to 0.86 cycles/cm (1 cycle = one black and one white stripe). Testing was conducted at a distance of 1.5 meters. At this distance, the stripe widths range from 104 to 2.3 cycles per degree of visual angle. The book was organized from widest to finest stripes, interleaving horizontal, vertical, and oblique stripes together to reduce the chance that differences in measurements across orientations might be obtained due to subject fatigue (or boredom) if testing of one orientation were completed prior to testing of the second orientation. Thus, subjects completed the trials for the widest horizontal, vertical, and oblique stripes for the largest spatial frequency stripes, then proceeded to the next finer stripe width for each orientation, etc.

In order to further reduce testing time and subject fatigue, the tester started with the 6.5 cy/cm stripes and asked subjects to complete only the first trial at each stripe width until the he or she incorrectly identified the location of the stripes on a trial (any orientation). The tester then went back two stripe widths (wider stripes) for all three orientations and from then on required the subject to correctly identify the location of the stripes on at least three of four trials for each orientation/stripe width before continuing on to the next finer stripe width for that orientation. If the child failed to identify stripe location on three out of four trials for one orientation of a particular stripe width but correctly identified stripe location on three out of four trials on one or both of the other orientations, testing progressed to fine stripe widths only for those remaining orientations on which the child continued to correctly identify the stripes. Grating acuity for each line orientation was scored as the highest spatial frequency stripes (finest stripe width) on which a subject could correctly locate the stripes on at least three of four trials.

Vernier Acuity. Horizontal, vertical and oblique vernier acuity stimuli were generated using a computer program and printed on a laser printer with a resolution of 600 dpi (stimuli designed by and program written by Joseph M. Miller, M.D., Miller, Harvey, and Dobson, 2002). An illustration of the test stimuli and of the test being conducted are shown in Figure 5. The figure of the test stimuli includes all four trials for a single level vernier offset for vertical stimuli. Ten vernier offset sizes were used. At a test distance of 1.75 meters, these offsets range from 120 arc sec to 5 arc sec. The stimuli were printed, mounted, and organized into a test book. Like the grating acuity stimulus book, horizontal, vertical, and oblique vernier stimuli were interleaved throughout the book, and it was organized from largest to smallest vernier offset.

The test design was essentially the same as that which was described for grating acuity, except here the subject's task was to identify which circle (top, middle, or bottom, or one, two, or three) contains the "wiggly" line. The tester began with the largest offset size, and ask subjects to complete only the first trial for each offset size/ line orientation in descending order of offset size until he or she incorrectly identified the location of a vernier offset on one of the orientations. The tester then went back two offset sizes (larger offsets) for all three orientations, and from then on for each level of vernier offset/orientation, required subjects to correctly identify the vernier offset in a 3AFC task on three out of four trials for each line orientation before continuing on to the next smaller size for that orientation. Vernier acuity for each line orientation was scored as the smallest vernier offset at which the child could correctly identify the vernier stimulus on three of four trials.

Contrast Sensitivity. Contrast sensitivity for horizontal and vertical stripes was determined for three different grating spatial frequencies: 1.5, 6, and 18 cycles/degree at a test distance of 10 feet. Contrast sensitivity stimuli were constructed from a commercially available clinical test of contrast sensitivity, the VCTS6500 Contrast Sensitivity Chart (Vistech Consultants, Inc., LaSalle, IL). The task requires subjects to identify the orientation of grating stimuli, which in the original version of the test are either vertical, or rotated 15 degrees clockwise or counter-clockwise from vertical. The original configuration of the test includes only vertical stimuli, and only one trial for each level of contrast/spatial frequency. Therefore, several charts were purchased, and were used to construct three test books (one for each of the three spatial frequencies (stripe widths) that contained four trials at each contrast level/orientation (horizontal/vertical). An example of four contrast sensitivity trials for a single stripe width (spatial frequency), contrast level, and stimulus orientation (horizontal) is shown in Figure 6, along with a photo of the test being conducted. The test design was similar to that which was used to test vernier acuity and grating acuity: each trial was a 3AFC task (horizontal, rotated clockwise, or rotated counter-clockwise in the example shown, or vertical, rotated clockwise, or rotated counter-clockwise (not shown)), and the subject must correctly identify the stripe orientation on at least three of four trials before continuing on to the next contrast level for that orientation. Horizontal and vertical stimuli were interleaved within the test book.

Pilot testing indicated that children can most reliably perform this task by holding up a pen in front of them, and matching the orientation of the pen to the orientation of the stripes. The tester began with one of the three spatial frequency stimulus books and presented the first trial at each contrast level/stripe orientation starting with the highest contrast level and proceeding sequentially towards lower contrast levels, until the child incorrectly identified the orientation of a stimulus. The tester then went back two contrast levels for both orientations, and from then on required the child to correctly identify the orientation of the stripes on at least three of four trials before continuing on to the next lower contrast level for an orientation. Contrast sensitivity for each stripe orientation for a given spatial frequency (stripe width) was scored as the lowest contrast level on which the child was able to correctly identify the orientation of the stripes on at least three of four trials. Order of testing across spatial frequency (1.5, 6, and 18 cycles per degree) was counterbalanced across subjects, and each child was tested in the same order at baseline, 1 month, and 1 year.

Stereoacuity. Stereoacuity was assessed using the Randot Preschool Stereoacuity Test (Stereo Optical Co., Chicago, IL), a commercially available clinical test of stereoacuity that utilizes random dot stimuli in order to assess stereoacuity in the absence of monocular depth cues. Since there is a wide age range included in the present study, the Randot Preschool Stereoacuity test was chosen so that all subjects would be able to perform the task. The stereoacuity test included six levels of retinal disparity that range from 800 to 40 seconds of arc, presented in three test books. For testing of stereoacuity, subjects wore specially constructed polarized glasses over their eyeglasses. It is these polarized glasses that cause retinal disparity for the random dot display, i.e., they cause slightly different images to be seen by the right and left eyes. A photo of a child being tested is shown in Figure 7.

Beginning with the largest disparity level, subjects were required to identify at least two of three shapes (e.g., star, house, duck) that appear in a random dot display. The random dot display is presented on the right side of the book, and the possible forms that can appear are shown in silhouette form on the left side of the book. Therefore, subjects could respond either verbally, or could point to the form on the left that they see in the random dot display on the right. Once a subject correctly identified at least two of three forms at a given disparity level, the tester will then continued on to the next finer disparity level, until subject was unable to correctly identify at least two shapes. Stereoacuity was recorded as the smallest disparity at which the subject could correctly identify two of three shapes in the random dot display.

Monocular Form Perception. Stimuli for evaluation of monocular form perception were created using Paintshop Pro computer software, and were presented on a laptop computer. The stimuli were generated from an image of an outline of a circle, and an outline of a circle filled in with a checkerboard pattern. Each of these two standard stimuli were distorted along the vertical axis to generate additional test stimuli. In total, 24 stimuli were generated from each standard: 12 that were elongated (made taller) and 12 that were reduced (made flatter) from the standard versions in 1% increments (i.e.

from 1% distortion to 12% distortion). From these stimuli, two Microsoft PowerPoint slide shows were generated: one for the outline circle and one for the checkerboard circle. Each page of the slide show contained a single stimulus centered on the screen, and the pages were ordered in terms of distortion from +12% (circle elongated vertically) to -12% (circle shortened vertically).

Subjects were told that their task was to adjust the stimulus until they found the one that looked perfectly round, like a ball rather than an egg, and to tell the experimenter once they had decided which one was the perfect circle. Stimuli were presented on a laptop computer, and the keyboard was covered with the exception of two keys: the page-up key, and the page-down key. Subjects were instructed that they should press the top key to make the "circle" taller, and press the bottom key to make the "circle" flatter.

Subjects participated in eight trials: four trials with their glass-on, and four with their glasses off. For each of the two glasses conditions (glasses on/off), there were two trials for each stimulus type (outline/checkerboard). For each stimulus type, one trial started from the most vertically elongated version (+12%), and one trial started from the most vertically shortened stimulus (-12%). After each trial, the experimenter recorded which stimulus the subject chose as "the perfect circle". Subjects were not given feedback regarding how close they were to finding the "correct" circle, but they were encouraged to take their time and make sure they found the "perfect circle". Order of testing (glasses on trials first or second) and stimulus order was randomized across subjects, and subjects conducted the test in the same order at baseline and at 1 month.

2.2.3 Data Analysis and Predictions

Subjects with ocular abnormalities other than myopia (nearsightedness) and hyperopia (farsightedness) and astigmatism were excluded from analyses. In addition, since predictions for astigmatic children are based on the presence of with-the-rule astigmatism (plus cylinder axis 90+/- 15 degrees), any astigmatic children with astigmatism that was not with-the-rule were also excluded from analyses.

Subjects were assigned to either the control group or the experimental group based on the results of the eye examination. Subjects with high astigmatism (>/= 1.00 Diopter in the right eye were assigned to the experimental group, and subjects with low or no astigmatism (< 1.00 Diopter in the right eye and left eye) were included in the control group. Subjects in the experimental group were further divided into two subgroups based on the type of astigmatism present: one group included subjects with myopic or mixed astigmatism (Figure 2d, 2e, and 2f), and the other included subjects with hyperopic astigmatism (Figure 2g and 2h).

Analyses are divided into three main sections. The first two sections address the secondary goals of the study, but because they entail analyses of baseline data, they are presented first in order to maintain the sequential logic of the study design. The first section addresses normal development across each aspect of vision and includes only control group subjects. The second section addresses the effects of astigmatism-related deprivation on visual development and initial measures of perception under conditions of spatial distortion and includes only baseline data comparing the astigmatism groups to the control group. The final section addresses the primary goal of the present study, plasticity related to recovery from astigmatism-related deprivation and to adaptation to form distortion, and compares change in perception from baseline to 1 month and from baseline to 1 year for the control group and the astigmatism groups.

Before continuing on to the results, I will briefly summarize the predictions regarding evidence for plasticity for both recovery from deprivation and for form adaptation. For measures of plasticity associated with recovery from astigmatism-related deprivation, I first predict that perceptual performance at baseline will be poorer for the astigmatism groups than for the control group. More specifically, for grating acuity, vernier acuity, and contrast sensitivity, measures on which I have included stimuli across different orientations, patterns of deficits observed should be dependent on the type of astigmatism present. That is, the stimulus orientation that is furthest from focus on the retina (horizontal for myopic and vertical for hyperopic astigmats) or more myopic in the case of mixed astigmatism (horizontal) when the astigmatism is uncorrected is the stimulus orientation for which subjects experienced the greatest and more consistent deprivation of clear visual input, and is therefore the stimulus orientation for which they should demonstrate deficits once the astigmatism is corrected. If there is plasticity for recovery from the effects of astigmatism-related deprivation in children of this age range, there should be greater improvement from baseline to 1 month and greater improvement from baseline to 1 year in children in the astigmatism groups than in children in the control group.

Similarly, for determination of plasticity associated with form adaptation, analyses focus on change from baseline to 1 month for the astigmatism groups in comparison to the control group. However, analysis of baseline data will first help determine if the children experience the distortion induced by the cylinder lenses, and if those distortions our measurable using the procedures implemented in the present study. Because cylinder lenses that correct for with-the-rule astigmatism have the effect of shortening perception of stimuli along one axis (flattening, as shown in Figure 8b), true circles should appear to be ovals when glasses are first worn by subjects in the experimental group. Thus, it is likely that astigmatic subjects will tend to perceive stimuli that are vertically elongated as more circle-like, because the elongation along the vertical axis present in the actual stimulus will essentially balance out the effect of the horizontal flattening induced by the lens, resulting in a perceived circle. Thus, for baseline measurements, the prediction is that that children in the control group, both with and without glasses on (because their glasses have little or no cylinder in the lenses), and children in the astigmatism group performing the task without their glasses on will be likely to identify stimuli close to the actual circle as their "perfect circle". Furthermore, children in the astigmatism group when wearing their glasses (with high cylinder in them) will be likely to choose an oval that is most likely to result in a percept of circle, based on the optics of the cylinder lens they are wearing (i.e., the vertically elongated circle). This pattern of results will confirm that the cylinder lenses that correct for astigmatism distort form perception, and that the distortion is measurable via this technique.

In the present study, I measured both "reduction of effect" and "negative aftereffects" for form adaptation. In measurements of reduction of effect, baseline and post-exposure measurements are made under conditions of altered sensory experience: perception is measured when the altered sensory experience is first induced (i.e., when glasses are first dispensed), and then after prolonged exposure (i.e., after 1 month of glasses wear). In measurements of negative aftereffects, baseline and post-exposure measurements are made under typical conditions: perception is measured prior to the introduction of the altered sensory experience, and then after the altered sensory conditions are removed. Measurements at baseline and follow-up were obtained under conditions of altered sensory experience (while subjects are wearing eyeglasses), and under unaltered sensory experience (while the subjects were not wearing eyeglasses). While measurements of negative aftereffects are the preferred measure of perceptual adaptation, the presence of sensory deprivation (blur induced by astigmatism) under unaltered sensory conditions in the present study makes measurements of "aftereffects" difficult. However, since subjects are likely to be able to perform the monocular form adaptation task even without their glasses on, I measured both "reduction of effect" and "negative aftereffects" for monocular form adaptation: measures at baseline and 1 month were conducted both with and without eyeglasses.

At the 1 month follow-up session, control group subjects will be expected to perform as they did at baseline: they will identify circles close to the actual circle as their "perfect circle" both with and without their glasses on. However, if plasticity exists for monocular form perception as a result of 1 month of cylinder lens wear, subjects in the astigmatism group will become more likely to choose stimuli that are less vertically elongated than those that they chose at baseline, both with and without their glasses on.

This result would demonstrate adaptation both in terms of "reduction of effect", i.e., with their glasses on, they will demonstrate a reduced perceptual distortion from baseline to follow-up when tested with their glasses on, and a "negative aftereffect, i.e., without their glasses on, they will tend to choose an oval that is distorted in the opposite direction as the distortion induced by the glasses.

2.3 Results

A total of 157 children were enrolled in the study. Of these children, 12 were excluded from analyses for the following reasons: child refused eye drops (n=1), exotropia (n=2), active conjunctivitis (n=1), blepharophimosis (n=1), iris coloboma (n=1), ptosis (n=1), astigmatism present, but axis was not with-the-rule (n=1), did not meet criteria for either the control or astigmatism group (RE astigmatism < 1, LE astigmatism >/= 1, n=4), prescription found to require adjustment after first eye exam (n=1). Thus, the final sample consisted of 144 children in grades K-8. The children ranged in age from 5.4 to 14.4 years of age (mean = 9.4 years, SD = 2.7), and 53% of the children were female.

Based on the results of the eye examination, children were assigned to groups. Of the 144 children, 96 were assigned to the control group (right eye and left eye astigmatism < 1.00 D), 29 were assigned to the myopic/mixed astigmatism group (right eye astigmatism >/= 1.00 D, and plus cylinder sphere < 0), and 19 were assigned to the hyperopic astigmatism group (right eye astigmatism >/= 1.00 D, and plus cylinder sphere >/= 0). The prevalence of high astigmatism found in this sample (33%, 48/144) is remarkably consistent with previous research, which also found the prevalence of high astigmatism in Tohono O'Odham preschool children to be approximately one-third (Dobson, Miller, and Harvey, 1999, Miller, Dobson, Harvey, and Sherrill, 2001).

There were significant differences among groups with regard to age ($F(2,141)=6.19$, $p=0.003$). Post-hoc comparisons indicated that the hyperopic group (mean=7.85, SD 2.07) was significantly younger than the myopic/mixed group (10.52, SD 2.41) and the control group (9.42, SD 2.70), although the myopic/mixed group did not differ significantly from the control group. This pattern is consistent with previous research on changes in refractive error with age which indicates that hyperopia is more prevalent in infancy and early childhood, and tends to decrease through mid to late childhood (for summary, see Zadnik and Mutti, 1998). Since age differences existed across groups, analyses were conducted with age entered as a covariate to reduce the possibility that significant differences among groups might be due to differences in age (differences in level of development), rather than to differences in visual experience (i.e., type of astigmatism present). Amount of astigmatism did not significantly differ between the myopic/mixed (mean = 2.84 diopters, SD=1.60, range = 1.00 to 8.25) and hyperopic groups (mean = 2.33 diopters, SD =1.27, range = 1.00 to 5.25) ($p=0.24$).

Sample sizes at the two follow-up points were reduced relative to baseline. Of 144 children in the final baseline sample, 141 (98%) participated in the 1 month follow-up. At the 1 year follow-up, the sample size was reduced to 84/144 (58%) for several reasons: (1) attempts were not made to follow the 8th grade class which had graduated and gone on to other schools, nor were attempts made to follow several children who were no longer enrolled in the school when we returned the second year for testing; (2) parents of one child refused participation in year 2; and (3) some children were newly enrolled in the school during year two of the study, and therefore baseline and 1 month data were collected in year two rather than 1 year follow-up data (this had the effect of increasing the sample size for baseline and 1 month data, but reducing the % follow-up for 1 year follow-up).

2.3.1 Baseline Data Analysis: Normal Development in 5- to 14-year-olds

Since, as a secondary research goal, I was interested in evaluating normal developmental trends for each of the measures of vision in the developmental analysis, these analyses were conducted only on children in the control group, i.e., children who had structurally normal eyes with no potentially amblyogenic conditions. This section contains detailed results of statistical analyses. A general summary and interpretation of results is provided at the end of the Results Section.

Figures 9-14 plot individual data and means on each measure by age. Table 1 ranks the results of correlation between age and each measure from lowest to highest. While some correlations appeared stronger than others, statistical analyses indicated that there was a significant relation between age and performance on each measure, with the exception of stereoacuity ($p < 0.08$).

In order to provide a more fine grained analysis of when significant development in each of these perceptual functions is occurring within this 5- to 14-year-old age range, I conducted ANOVAs on each measure to compare performance across several age categories: 5- and 6-year-olds, 7- and 8-year-olds, 9- and 10-year-olds, and

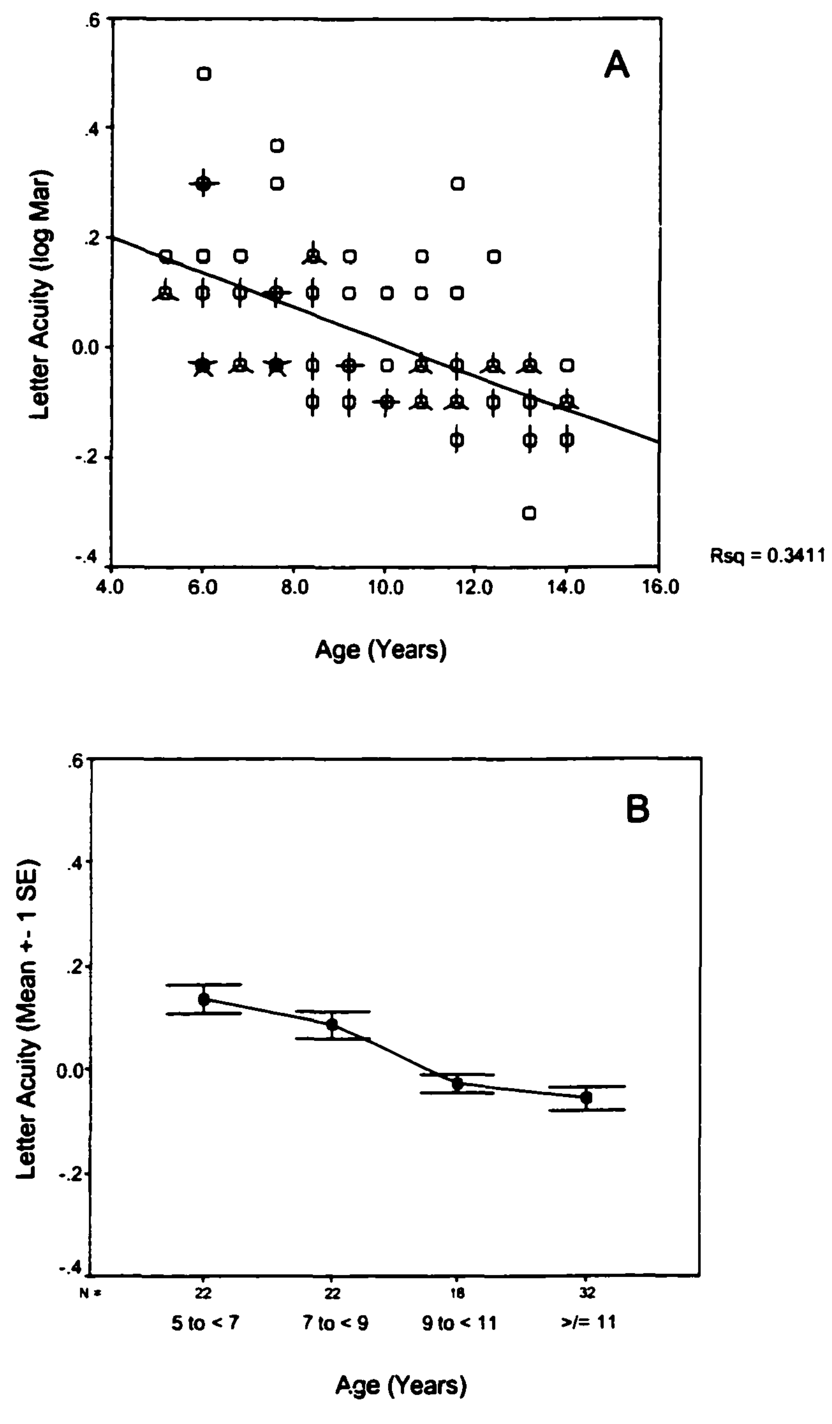


Figure 9. Recognition (letter) acuity by age. Individual data are plotted in A, and means +/- 1 standard error are plotted in B. In A, each line on the symbols represents data from one subject.

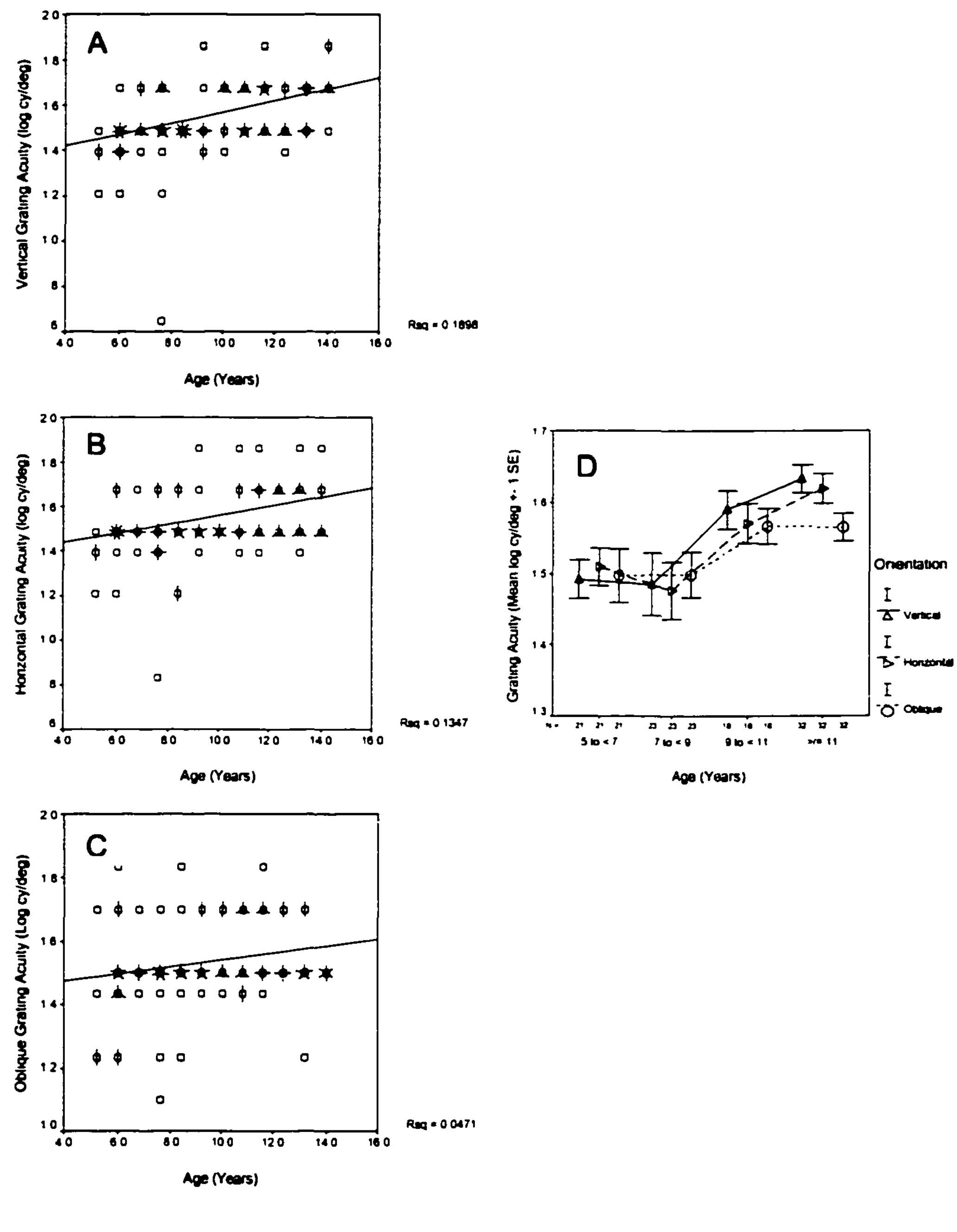


Figure 10. Resolution (grating) acuity by age. Individual data are plotted in A, B, and C for vertical, horizontal and oblique stimuli, respectively. Each line on the symbols represents data from one subject. Means +/- 1 standard error are plotted in D.

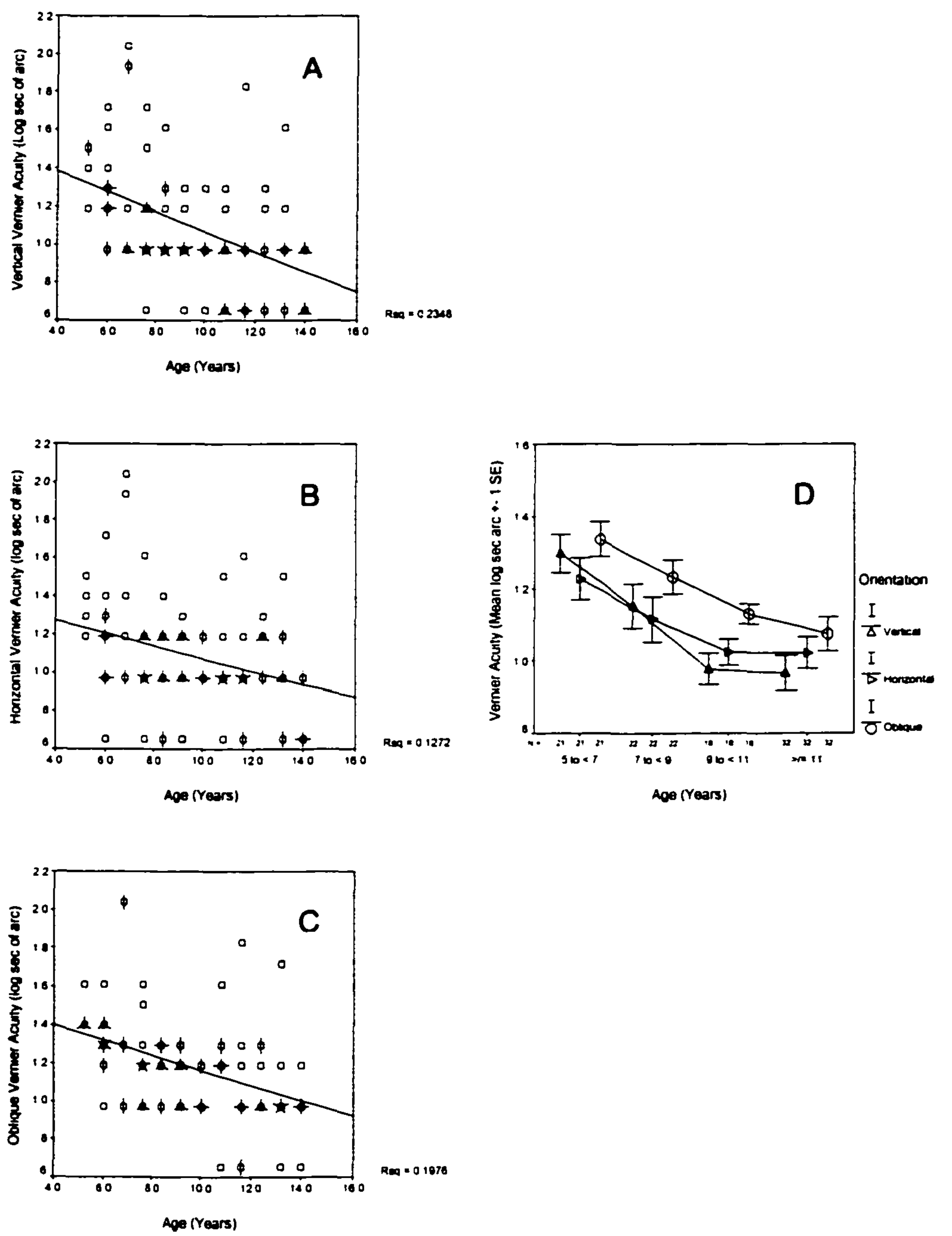


Figure 11. Vernier acuity by age. Individual data are plotted in A, B, and C for vertical, horizontal and oblique stimuli, respectively. Each line on the symbols represents data from one subject. Means +/- 1 standard error are plotted in D.

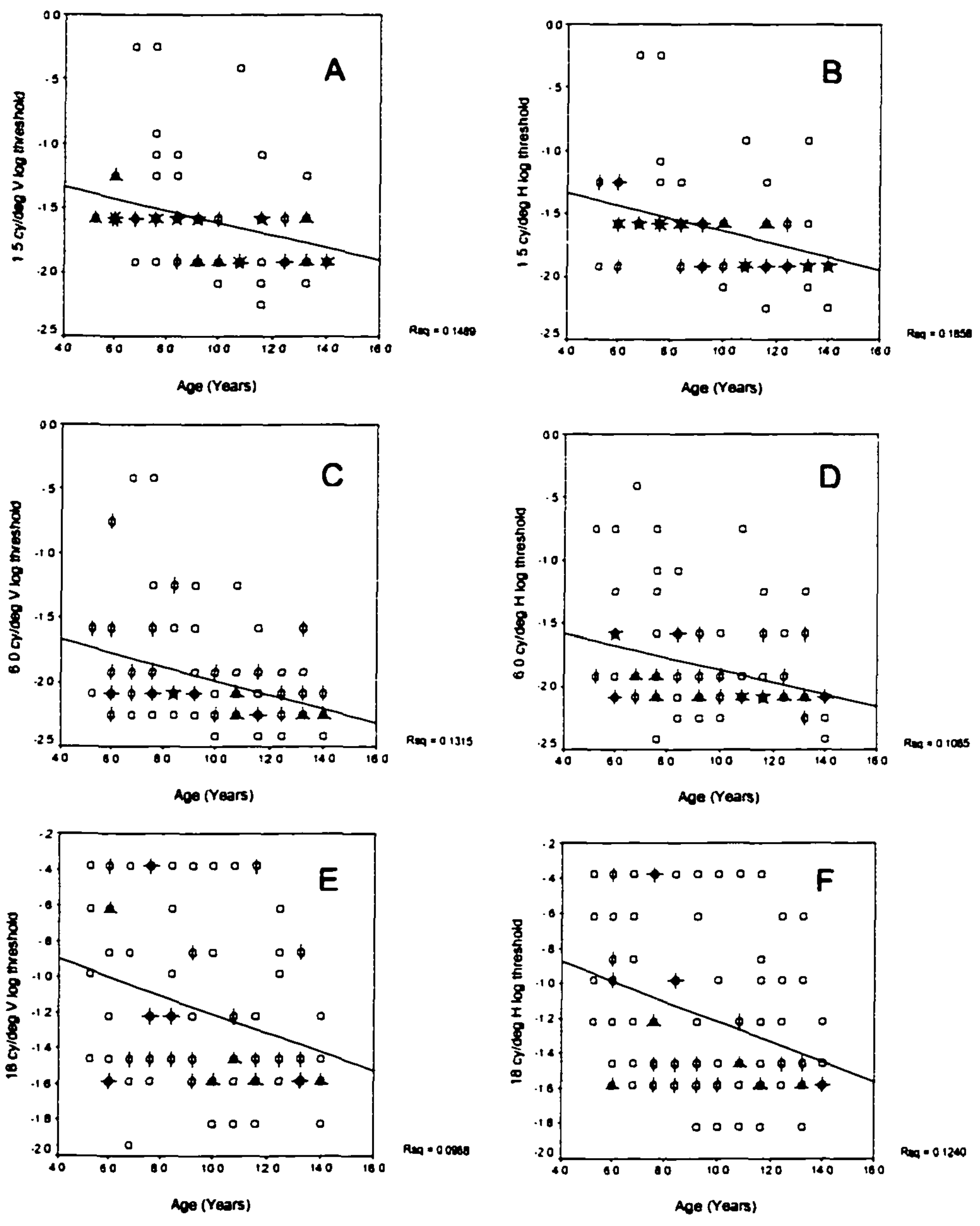
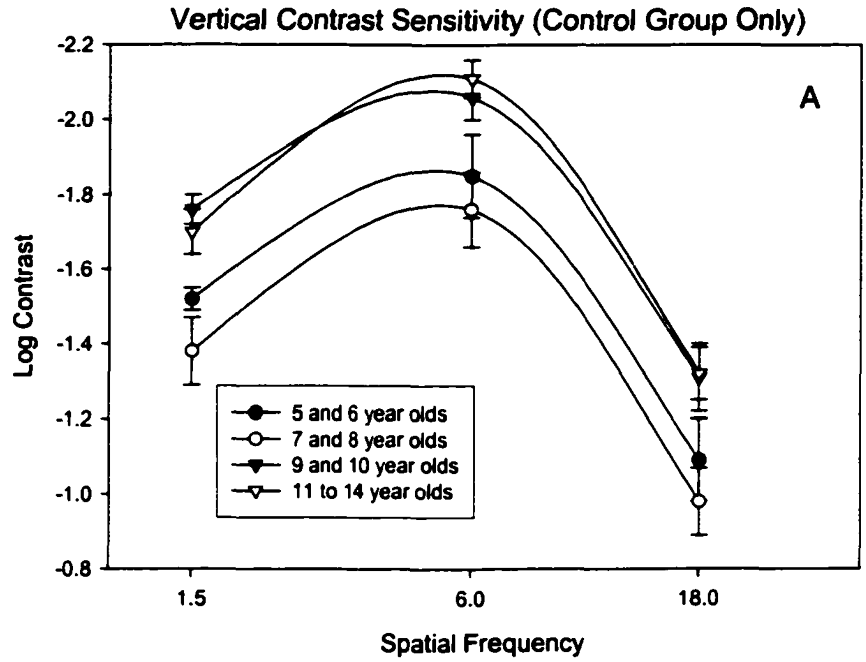


Figure 12. Contrast sensitivity by age. Individual data are plotted in A and B for low spatial frequency stimuli, C and D for middle spatial frequency stimuli, and E and F for High spatial frequency stimuli. Data for vertical stimuli are plotted in A, C, and E, data for horizontal stimuli are plotted in B, D, and F.



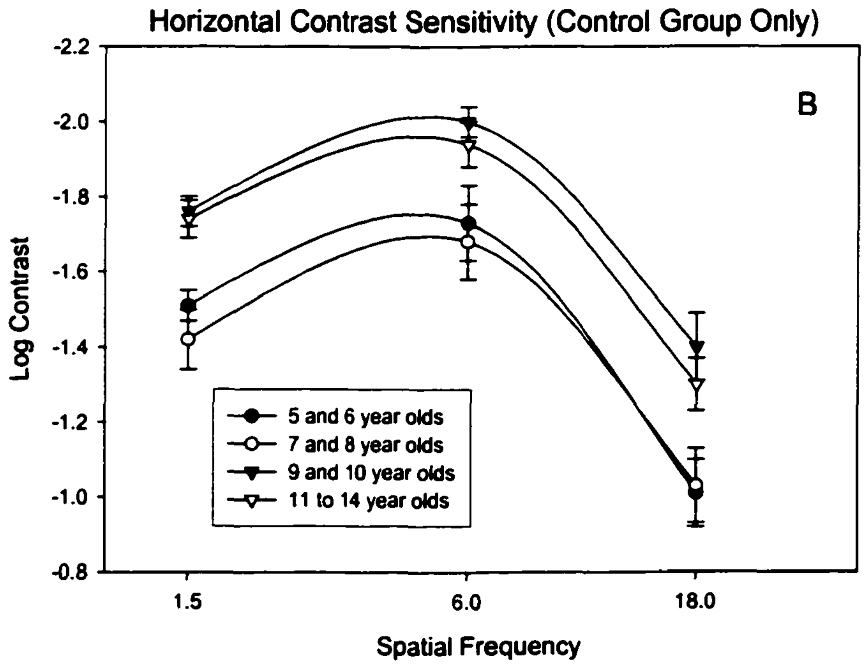


Figure 13. Mean Contrast sensitivity by age and spatial frequency. Means +/- 1 standard error for vertical stimuli (A) and horizontal stimuli (B).

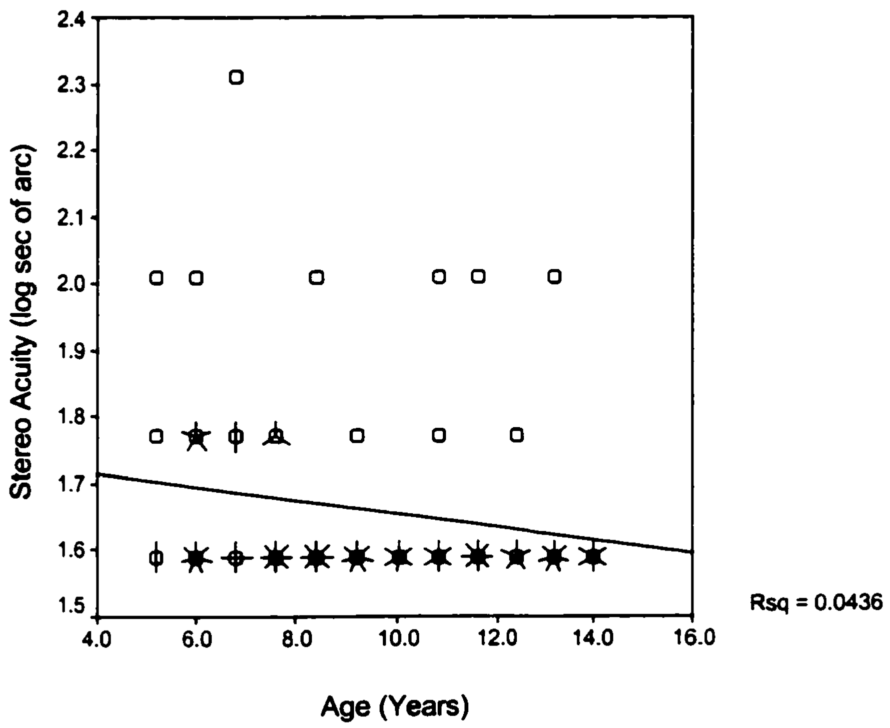


Figure 14. Stereoacuity by age. Each line on the symbols represents data from one subject.

Table 1. Correlations between age and measures of perception.

Measure	Correlation
Stereoacuity	0.15
Grating Acuity – Oblique	0.18 *
18 cy/deg Contrast Sensitivity – Vertical	0.27 *
6 cy/deg Contrast Sensitivity – Horizontal	0.30 *
18 cy/deg Contrast Sensitivity – Horizontal	0.32 *
Vernier Acuity – Horizontal	0.33 *
6 cy/deg Contrast Sensitivity – Vertical	0.34 *
1.5 cy/deg Contrast Sensitivity – Vertical	0.38 *
Grating Acuity – Horizontal	0.39 *
Grating Acuity – Vertical	0.41 *
Vernier Acuity – Oblique	0.42 *
1.5 cy/deg Contrast Sensitivity – Horizontal	0.43 *
Vernier Acuity – Vertical	0.46 *
Letter Acuity	0.58 *

* $P < 0.01$

11- to 14-year-olds. Plots of means by age are provided for each age in Figures 9-14. ANOVAs on each of the measures indicated a significant main effect of age group for all measures with the exception of stereoacuity (which approached significance, $p=0.06$) and grating acuity for oblique stimuli ($p=0.13$).

In order to narrow down the age range during which most development was occurring, post-hoc comparisons focused first on determining if there were significant improvements between adjacent age groups (5/6 vs. 7/8, 7/8 vs. 9/10, 9/10 vs. 11+). For letter acuity, the ANOVA showed a significant main effect of age group ($F(3,93)=13.87$, $p < 0.001$), and post-hoc comparisons indicated that there was significant improvement between the 7/8 and 9/10 age groups ($p = 0.024$), but not between other adjacent groups. This finding is apparent in the plot of means, which shows a greater slope between the means for these two age groups.

For vertical and horizontal grating acuity, there were significant main effects of age group ($F(3,93)=6.58$, $p< 0.001$ for vertical and $F(3,93)=5.45$, $p= 0.002$ for horizontal). There was no significant difference between adjacent age groups, but there was significant change from 5/6 to 11+ ($p=0.005$ for horizontal and $p=0.038$ for vertical), and from 7/8 to 11+ ($ps=0.002$). Thus, as can be seen in the plot of means for vertical and horizontal grating acuity, much of the development occurs between the 7/8 and 11+ age groups, suggesting gradual improvement between ages 7 and 11+. As previously noted, no main effect of age group was observed for grating acuity for oblique stimuli, although the general shape of the developmental function is similar to that obtained for horizontal and vertical stimuli.

For vernier acuity, there was a significant main effect for age group ($F(3,94)=10.09$, $p< 0.001$, $F(3,92)=3.48$, $p=0.019$, and $F(3,93)=6.73$, $p <0.001$ for vertical, horizontal and oblique stimuli, respectively) but no significant improvement was observed between adjacent age groups. However, there was significant improvement between the 5/6 to 9/10, and the 7/8 to 11+ age groups for vertical ($p=0.001$ and $p=0.039$, respectively) and oblique stimuli ($p=0.029$ and $p=0.04$, respectively), and significant improvement from the 5/6 to the 11+ age groups for horizontal stimuli ($p=0.024$). Thus, even more so than for grating acuity, improvements in vernier acuity appear to be gradual across this age range.

Analyses revealed significant main effects of age group for contrast sensitivity for vertical and horizontal low spatial frequency stimuli ($F(3,91)=7.49$, $p < 0.001$ for vertical and $F(3,91)=8.14$, $p<0.001$ for horizontal), mid range spatial frequency stimuli ($F(3,91)=4.83$, $p=0.004$ for vertical and $F(3,91)=3.70$, $p=0.015$ for horizontal), and high spatial frequency stimuli ($F(3,92)=3.52$, $p=0.018$ for vertical and $F(3,92)=4.64$, $p=0.005$ for horizontal). Post-hoc analyses on contrast sensitivity for low spatial frequency vertical and horizontal stimuli indicated that there was significant improvement between the adjacent 7/8 and 9/10 age groups ($p=0.001$ for vertical and $p=0.002$ for horizontal). For mid range spatial frequency stimuli, improvement between the 7/8 and 9/10 year age groups for vertical and horizontal stimuli approached significance for both stimulus orientations (ps=0.09 and 0.05), and improvement from 7/8 to 11+ age groups was significant for vertical stimuli only ($p=0.006$). Finally, for the high spatial frequency stimuli, there was significant improvement for vertical stimuli between the 7/8 and 11+

age groups (p=0.034), with the 7/8 vs. 9/10 comparison approaching significance (p=0.11), and there was significant improvement for horizontal stimuli between the 7/8 and 9/10 year age groups (p=0.035). This pattern of results is clear in plots of mean contrast sensitivity in Figure 13, which show a relatively large jump in improvement between the 7/8 and 11+ age groups.

As previously noted, the significant main effect of age for stereoacuity approached statistical significance (p=0.063). Therefore, post-hoc comparisons for this measure were also conducted, and indicated a marginally significant improvement in stereoacuity between the 5/6 and 9/10 year age groups (p=0.055), suggesting small gradual improvement within the 5 to 10 year age range.

2.3.2 Baseline Data Analysis: Effects of Deprivation and Spatial Distortion on Perception

This section contains baseline comparisons between the control group and the astigmatism groups on baseline measures of perception, that is, perceptual performance when the children first put on their eyeglasses. For recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereo acuity, differences between the control and astigmatism groups reflect the influence of astigmatism on visual perceptual development. For measures of form perception, differences between the control and astigmatism group reflect the spatially distorting effects of the cylinder lenses used to correct for astigmatism. Separate analyses were conducted for each measure. This section contains detailed results of statistical analyses. For comparison across measures, a summary of baseline analyses is provided in Table 2, and a general summary and brief interpretation of results is provided at the end of the Results Section.

Table 2. Baseline Data Analysis Summary. All analyses conducted with age as a covariate to control for age (i.e., developmental differences) across groups. Sample sizes for the control, myopic/mixed, and hyperopic groups, respectively, provided in parenthesis.

Measure (sample sizes)		3 Groups ANOVAs		Post-Hoc Tests: Control vs. Myopic/ Mixed	Post-Hoc Tests: Control vs. Hyperopic	Post-Hoc Tests: Myopic/ Mixed vs. Hyperopic
Letter Acuity (94,28,19)		Group * (<0.001)		* (<0.001)	* (<0.001)	NS (0.93)
Grating Acuity (94,28,18)	V	Orientation x Group * (=0.017)		* (=0.001)	* (=0.018)	NS (0.98)
	H			* (<0.001)	* (=0.028)	NS (0.13)
	O			* (<0.001)	* (<0.001)	NS (0.84)
	V-H			* (=0.029)	NS (0.73)	NS (0.16)
Vernier Acuity (93,27,19)	V	Group * (0<0.001) Orientation x Group (NS)		* (=0.003)	* (=0.003)	NS (0.31)
	H			* (=0.002)	* (=0.001)	NS (0.78)
	O			* (=0.001)	* (<0.001)	NS (0.20)
	V-H			NS (0.99)	NS (0.97)	NS (0.26)
Contrast Sensitivity 1.5 cy/deg	V	Orientation x Spatial Frequency x Group (=0.016)	Orientation x Group * (0.047)	NS (0.67)	NS (0.20)	NS (=0.08)
	H			NS (0.90)	* (0.004)	* (=0.012)
	V-H			NS (0.41)	* (0.028)	NS (0.26)
Contrast Sensitivity 6.0 cy/deg	V		Orientation x Group (NS)	* (=0.007)	* (<0.001)	NS (0.15)
	H			* (=0.002)	* (=0.001)	NS (0.30)
	V-H			NS (0.63)	NS (0.58)	NS (0.44)
Contrast Sensitivity 18.0 cy/deg	V		Orientation x Group * (=0.004)	* (<0.001)	* (<0.001)	NS (0.27)
	H			* (<0.001)	* (<0.001)	NS (0.99)
	V-H			* (=0.001)	NS (0.93)	NS (0.23)
Stereoacuity (95,28,18)		* (<0.001)		* (=0.037)	* (<0.001)	NS (0.062)

* Statistically significant before Bonferroni correction applied (p values represent uncorrected significance level).

V = Vertical Stimuli, H = Horizontal Stimuli, O = Oblique Stimuli, V-H =Vertical - Horizontal.

Recognition (Letter) Acuity: Sample sizes for baseline letter acuity measurements were 94, 28, and 19 for the control, myopic/mixed, and hyperopic groups, respectively. A scatter plot of individual subject data and a plot of group means is provided in Figure 15. For letter acuity, higher numbers represent poorer acuity, i.e., thresholds of higher logMAR values (minimum angle of resolution) represent poorer acuity. Mean acuity was 0.03 logMAR (SD 0.14) for the control group, 0.20 logMAR (SD 0.16) for the myopic/mixed group, and 0.25 logMAR (SD 0.22) for the hyperopic group. These mean logMAR values correspond to snellen values of 20/21 for the control group, 20/32 for the myopic/mixed group, and 20/36 for the hyperopic group. A one-way ANOVA yielded significant main effect of group ($F(2,141) = 26.76$, $p < 0.001$). Post-hoc analyses indicated that mean acuity was significantly reduced for the myopic/mixed and hyperopic groups in comparison to the control group ($ps < 0.001$), but the two astigmatism groups did not significantly differ from each other.

Resolution (Grating) Acuity: Sample sizes for baseline grating acuity measurements were 94, 28, and 18 for the control, myopic/mixed, and hyperopic groups, respectively. Means for each stimulus orientation by group are provided in Table 3, and scatter plots of individual subject data and a plot of group means is provided in Figure 16. For measures of grating acuity, higher numbers represent better grating acuity, i.e., thresholds of more cycles (1 cycle = one black and one white stripe) per degree of visual angle represent finer acuity. A repeated measures group by orientation ANOVA yielded a significant interaction between orientation and group ($F(4, 272) = 3.08$, $p < 0.02$). Post hoc analyses indicated that horizontal, vertical and oblique grating acuity for the

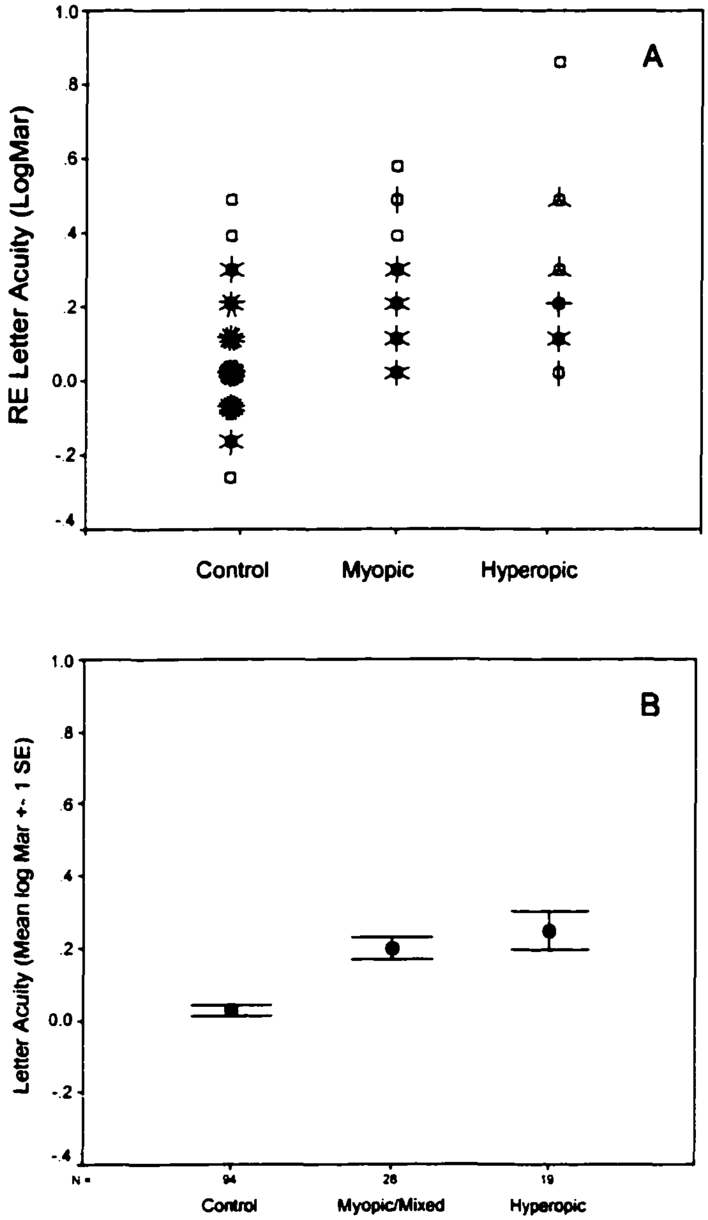


Figure 15. Baseline recognition (letter) acuity by group. Individual data are plotted in A, and means +/- 1 standard error are plotted in B. In A, each line on the symbols represents data from one subject.

Table 3. Baseline grating acuity means by group.

Stimulus Orientation	GROUP	Mean (log cy/deg)	Standard Deviation	N
Vertical	Control	1.5569	0.15765	94
	Myopic/Mixed	1.4794	0.12943	28
	Hyperopic	1.4214	0.20543	18
	Total	1.5240	0.16595	140
Horizontal	Control	1.5500	0.15015	94
	Myopic/Mixed	1.4014	0.15975	28
	Hyperopic	1.4400	0.13565	18
	Total	1.5061	0.16239	140
Oblique	Control	1.5337	0.13965	94
	Myopic/Mixed	1.3883	0.15321	28
	Hyperopic	1.3437	0.11067	18
	Total	1.4802	0.15860	140

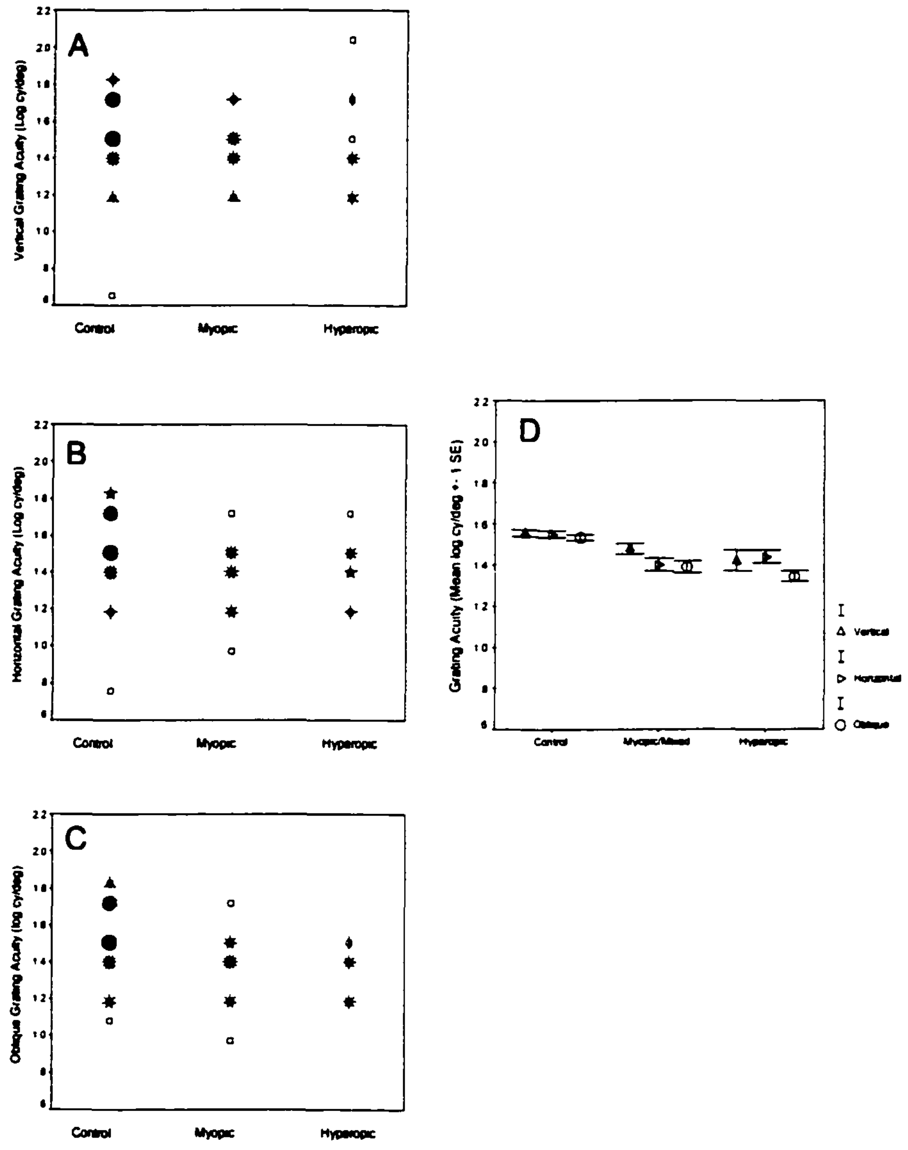


Figure 16. Baseline resolution (grating) acuity by group. Individual data are plotted in A, B, and C for vertical, horizontal and oblique stimuli, respectively. Means +/- 1 standard error are plotted in D.

myopic/mixed group was significantly poorer than for the control group. The difference between vertical and horizontal grating acuity was greater than this difference in the control group, although this comparison reached statistical significance before, but not after correction for multiple comparisons. Oblique grating acuity for the hyperopic group was significantly poorer than the control group, and while vertical and horizontal grating acuity were poorer in the hyperopic group than in the control group, these effects reached statistical significance before, but not after correction for multiple comparisons. The difference between vertical and horizontal grating acuity for the hyperopic group did not significantly differ from the control group. Myopic/mixed and hyperopic groups did not significantly differ on vertical, horizontal or oblique grating acuity, nor did they differ in the difference between vertical and horizontal grating acuity.

Vernier acuity: Sample sizes for baseline vernier acuity measurements were 93, 27, and 19 for the control, myopic/mixed, and hyperopic groups, respectively. Means for each stimulus orientation by group are provided in Table 4, and scatter plots of individual subject data and plots of means by group are provided in Figure 17. For vernier acuity, higher scores represent poorer acuity, i.e., thresholds of greater size (more seconds of arc) represent poorer vernier acuity. A group by orientation ANOVA yielded a significant main effect of group ($F(2, 135) = 11.83$, $p < 0.001$), but the main effect of orientation and group by orientation interaction was not significant. Post hoc analyses indicated that mean horizontal, vertical and oblique vernier acuity for the myopic/mixed group and for the hyperopic group were significantly poorer than for the control group, although the

Table 4. Baseline vernier acuity means by group.

Stimulus Orientation	GROUP	Mean (log sec of arc)	Standard Deviation	N
Vertical	Control	1.0860	0.28459	93
	Myopic/Mixed	1.2258	0.25720	27
	Hyperopic	1.3914	0.32326	19
	Total	1.1549	0.30328	139
Horizontal	Control	1.0897	0.25670	93
	Myopic/Mixed	1.2384	0.32278	27
	Hyperopic	1.3749	0.32374	19
	Total	1.1576	0.29684	139
Oblique	Control	1.1811	0.24281	93
	Myopic/Mixed	1.3262	0.24680	27
	Hyperopic	1.4745	0.28634	19
	Total	1.2494	0.26973	139

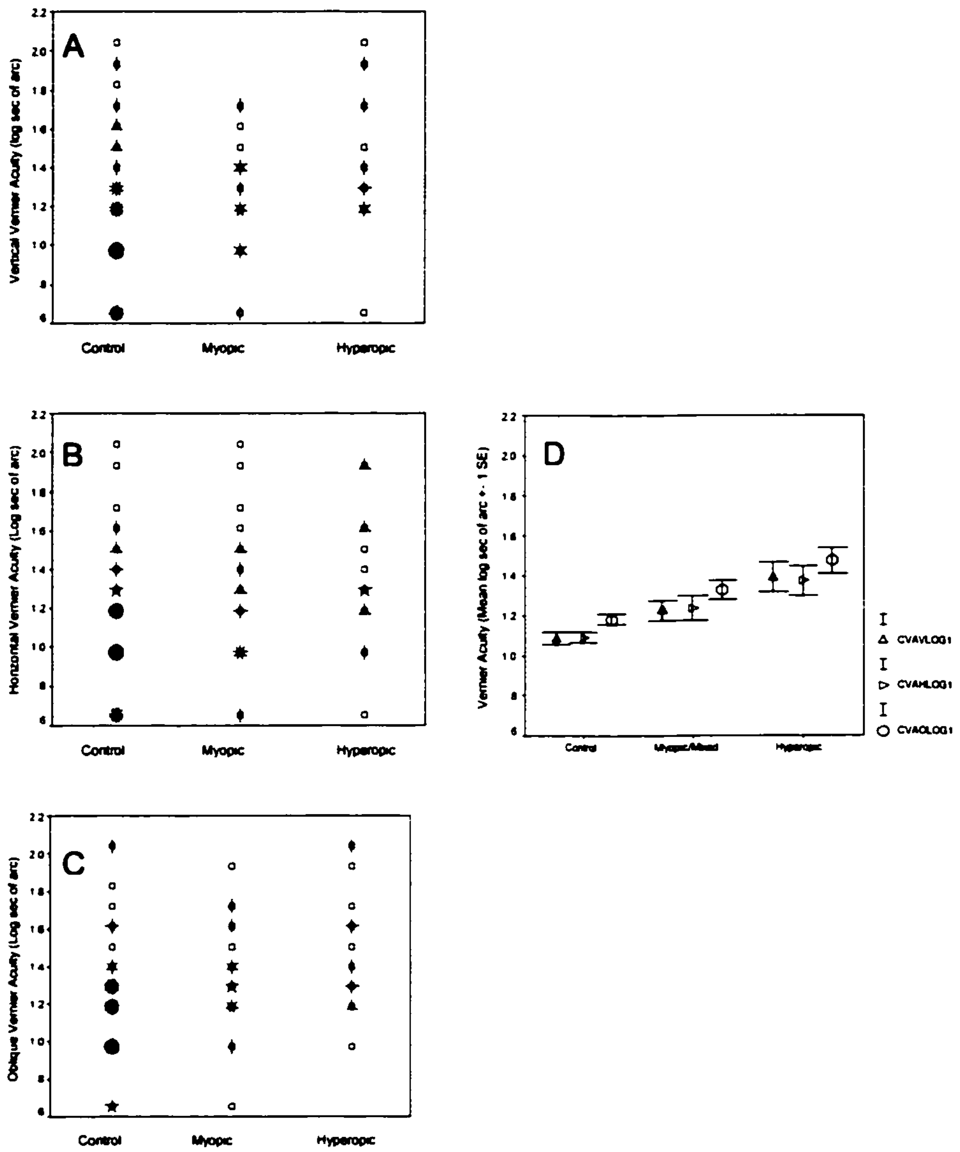


Figure 17. Baseline vernier acuity by group. Individual data are plotted in A, B, and C for vertical, horizontal and oblique stimuli, respectively. Means +/- 1 standard error are plotted in D.

astigmatism groups did not differ from each other. The difference between vertical and horizontal vernier acuity did not significantly differ from the control group for either the myopic/mixed or hyperopic groups, nor did the astigmatism groups differ from each other on this measure.

Contrast sensitivity. A summary of contrast sensitivity means is provided in Table 5, scatter plots of individual subject data are shown in Figure 18, and plots of mean data by group are shown in Figure 19. Higher contrast sensitivity values represent poorer contrast sensitivity, i.e., thresholds with greater percentage contrast values represent poorer contrast sensitivity. Separate analyses were conducted for each spatial frequency.

A group by orientation ANOVA on contrast sensitivity for low spatial frequency stimuli (1.5 cy/deg) yielded a significant orientation by group interaction ($F(2,134) = 3.14$, $p<0.05$). The myopic/mixed group did not differ from the control group on horizontal, vertical, or on the difference between horizontal and vertical contrast sensitivity. The hyperopic group had significantly poorer horizontal contrast sensitivity than the control group, but contrast sensitivity for vertical stimuli did not significantly differ from the control group, nor did the hyperopic and control groups differ on the difference between vertical and horizontal contrast sensitivity after correction for multiple comparisons was applied. Contrast sensitivity for vertical stimuli did not differ between myopic/mixed and hyperopic groups, and horizontal contrast sensitivity was poorer for the hyperopic group than the myopic/mixed group, although these effect did not reach statistical significance after correction was applied. The two astigmatism groups did not differ on difference between vertical and horizontal contrast sensitivity.

Table 5. Baseline contrast sensitivity means by group.

Stimulus	GROUP	Mean (Log CS)	Std. Deviation	N
1.5 cy/deg Vertical	Control	-1.59322	0.330356	92
	Myopic/Mixed	-1.66076	0.219898	29
	Hyperopic	-1.41164	0.452425	17
	Total	-1.58505	0.333570	138
1.5 cy/deg Horizontal	Control	-1.61797	0.321131	92
	Myopic/Mixed	-1.65216	0.182413	29
	Hyperopic	-1.28246	0.500514	17
	Total	-1.58382	0.342926	138
6.0 cy/deg Vertical	Control	-1.96401	0.402125	92
	Myopic/Mixed	-1.79139	0.350602	29
	Hyperopic	-1.48632	0.535774	17
	Total	-1.86889	0.437682	138
6.0 cy/deg Horizontal	Control	-1.84564	0.395783	92
	Myopic/Mixed	-1.64247	0.285723	29
	Hyperopic	-1.41251	0.507702	17
	Total	-1.74959	0.416605	138
18 cy/deg Vertical	Control	-1.18950	0.450867	92
	Myopic/Mixed	-.83865	0.404703	29
	Hyperopic	-.59876	0.304847	17
	Total	-1.04300	0.476542	138
18 cy/deg Horizontal	Control	-1.19484	0.439436	92
	Myopic/Mixed	-.63934	0.319904	29
	Hyperopic	-.60721	0.290817	17
	Total	-1.00572	0.480830	138

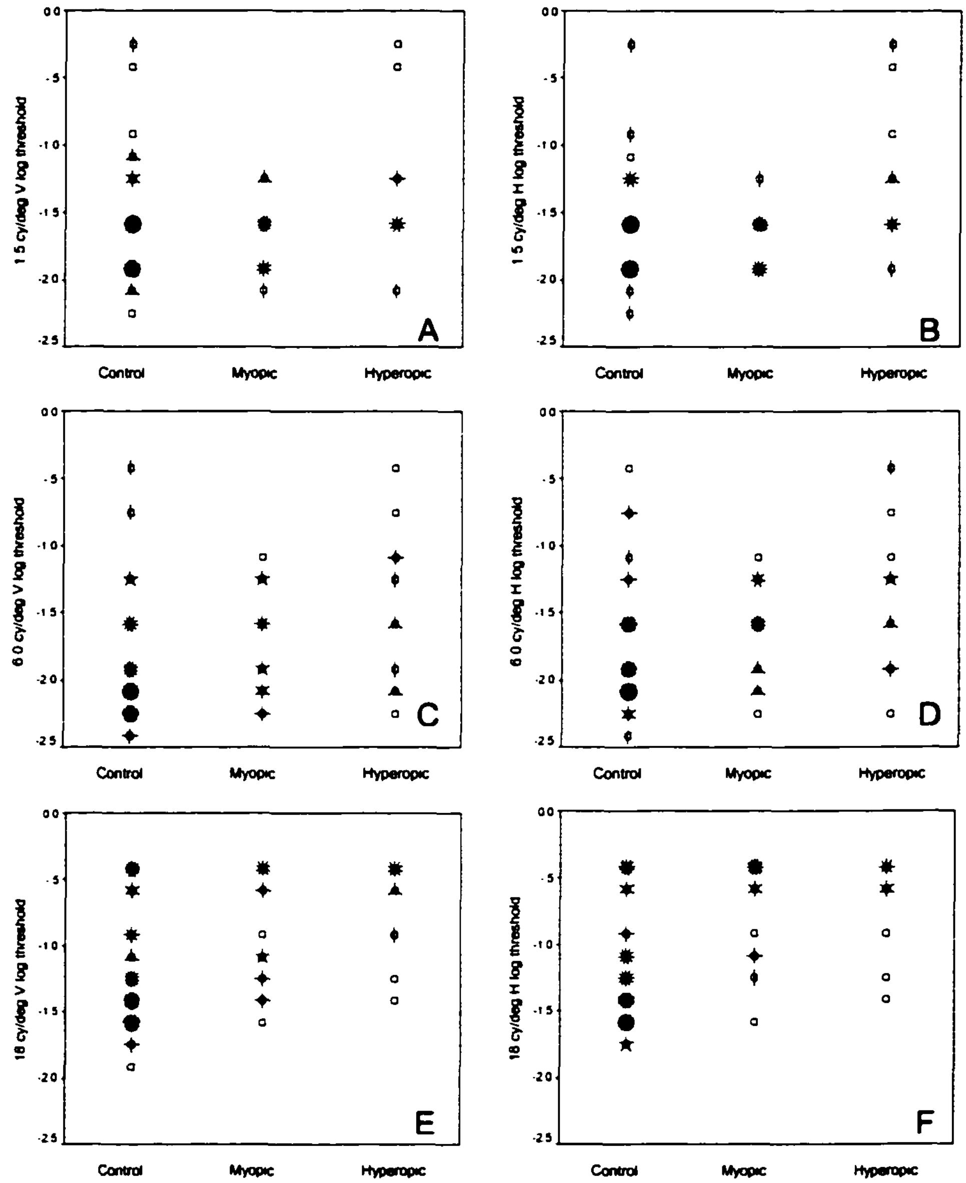


Figure 18. Baseline contrast sensitivity by group scatter plots. Individual data are plotted in A and B for low spatial frequency stimuli, C and D for middle spatial frequency stimuli, and E and F for High spatial frequency stimuli. Data for vertical stimuli are plotted in A, C, and E, data for horizontal stimuli are plotted in B, D, and F.

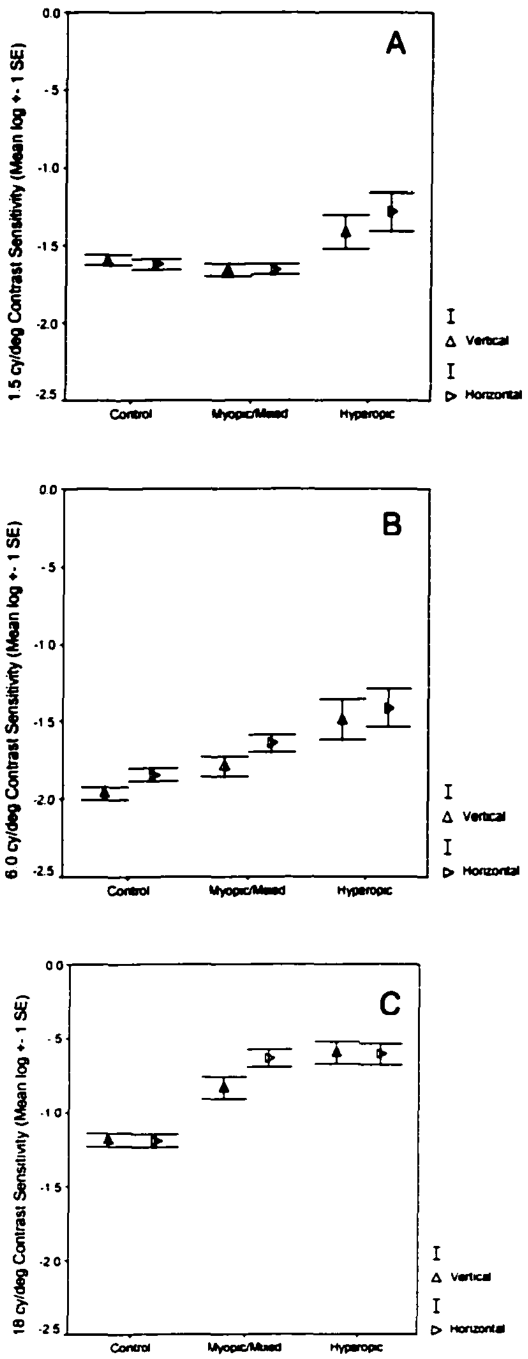


Figure 19. Baseline contrast sensitivity means by group. Means +/- 1 standard error for vertical and horizontal stimuli are plotted in A for low spatial frequency stimuli, B for middle spatial frequency stimuli, and C for high spatial frequency stimuli.

A group by orientation ANOVA on contrast sensitivity for middle spatial frequency stimuli (6.0 cy/deg) yielded a significant main effect of group ($F(2,134) = 10.80$, $p<0.001$), but no significant main effect of orientation or orientation by group interaction. Both the myopic/mixed and hyperopic groups differed from the control group on horizontal and vertical contrast sensitivity, but neither astigmatism group differed from the control group on the difference between vertical and horizontal contrast sensitivity. The myopic/mixed and hyperopic groups did not differ on any measure.

A group by orientation ANOVA on contrast sensitivity for high spatial frequency stimuli (18.0 cy/deg) yielded a significant orientation by group interaction ($F(2,135) = 5.82$, $p < 0.005$). Both the myopic/mixed and hyperopic groups differed from the control group on horizontal and vertical contrast sensitivity, but only the myopic/mixed group differed from the control group on V-H contrast sensitivity. The myopic/mixed and hyperopic groups did not differ on any measure.

Stereoacuity: Sample sizes for baseline stereoacuity measurements were 95, 28, and 18 for the control, myopic/mixed, and hyperopic groups, respectively. The mean stereoacuity for was 1.66 log sec (SD 0.13) for the control group, 1.72 log sec (SD 0.22) for the myopic/mixed group, and 1.91 log sec (SD 0.39) for the hyperopic group. Figure 20 plots individual stereoacuity scores and mean stereoacuity scores for each group. For stereoacuity measures, higher scores represent poorer stereoacuity, i.e., thresholds with larger difference (more seconds of arc) in images between eyes necessary to give rise to the perception of depth indicate poorer stereoacuity. A one-way ANOVA yielded a

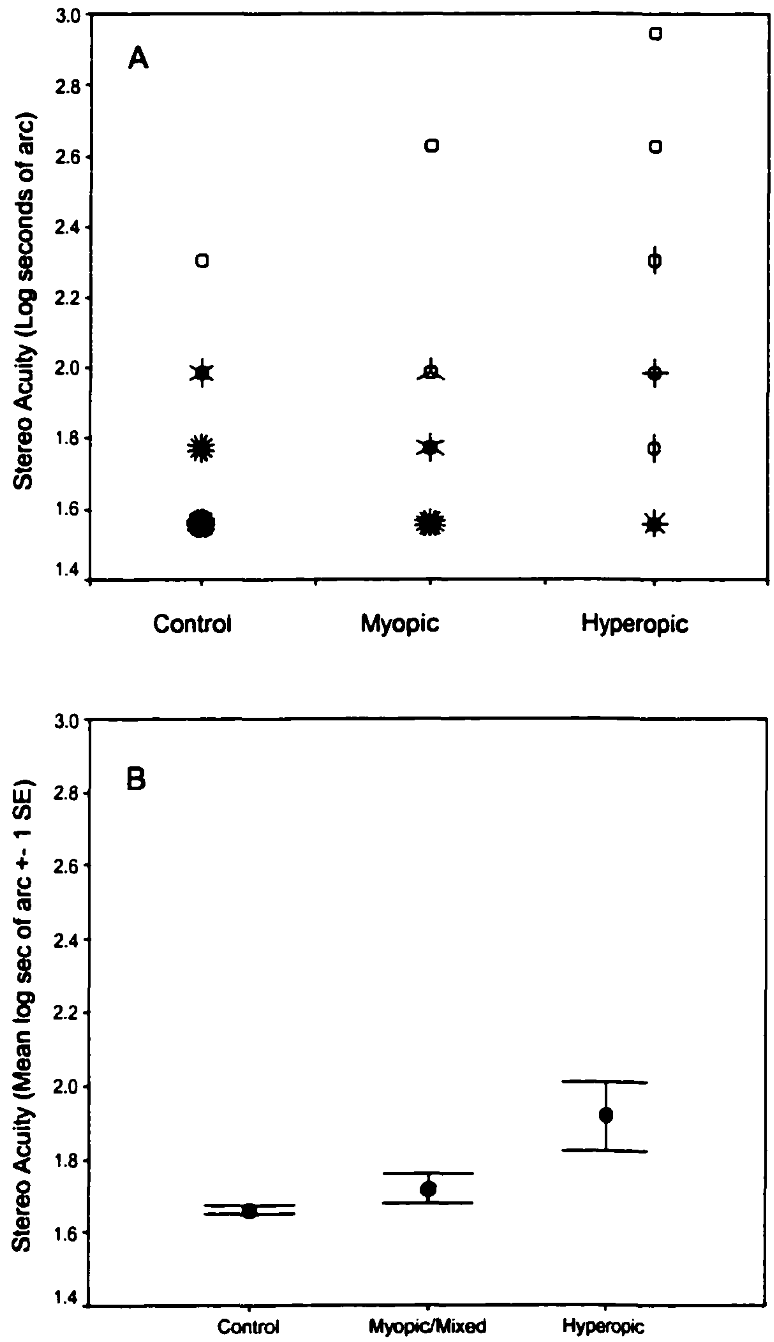


Figure 20. Baseline stereoacuity by group. Individual data are plotted in A, and means +/- 1 standard error are plotted in B. In A, each line on the symbols represents data from one subject.

significant main effect of group ($F(2, 137) = 11.38$, $p < 0.001$). Post-hoc analyses indicated that stereoacuity for the hyperopic group was significantly poorer than the control group. Other comparisons did not reach statistical significance: stereoacuity for the myopic/mixed group was not significantly reduced in comparison to the control group after correction for multiple comparisons, and stereoacuity for the hyperopic group was not significantly reduced in comparison to the myopic/mixed group.

Form Adaptation. For measurements of form perception, raw data ranged from –12 to +12 in whole numbers, with negative numbers representing vertically compressed circles, 0 representing a true circle, and positive numbers representing vertically elongated circles. Negative and positive numbers also represent the percentage that the stimulus is compressed or elongated, relative to a true circle, e.g., -6 represents a 6% vertically compressed circle.

Mean scores for each wear (glasses on/glasses off) condition at baseline were determined by averaging responses on four trials: two trials each for the outline circle and checkered circle stimuli, one on which the child started the task on the –12 stimulus, and one on which the child started the task on the +12 stimulus.

A group by wear repeated measures ANOVA was conducted on baseline data. Figure 21 illustrates the predicted pattern of results, along with the observed pattern of results. At baseline, I predicted that there would be no difference in mean response for the control group with glasses-on vs. glasses-off (since there is little or no cylinder in the lenses), and that the astigmatism group would not differ from the control group in the glasses-off condition at baseline. However, the astigmatism group, on average, should

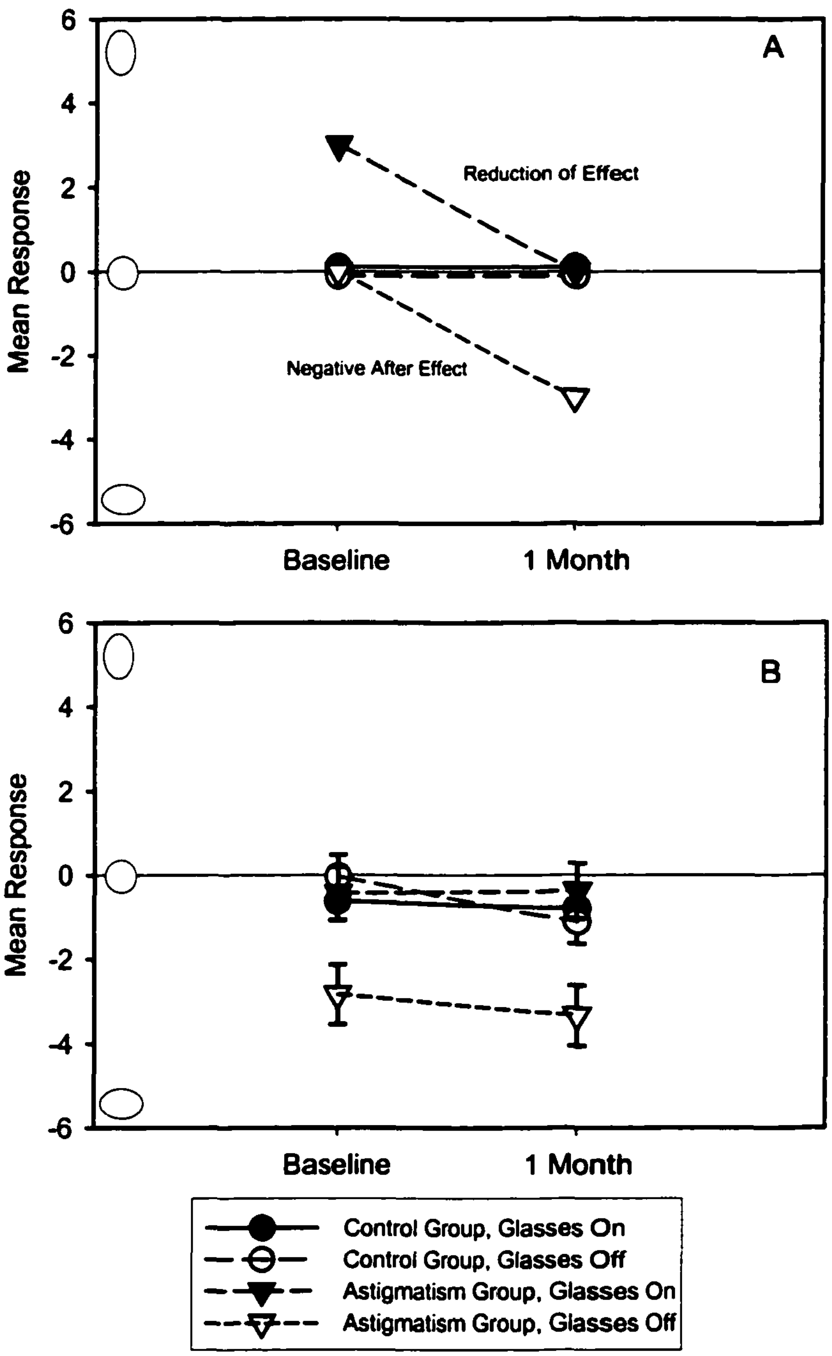


Figure 21. Predicted and observed form perception by time plots. Predicted patterns are shown in A, observed means +/- 1 standard error are shown in B.

tend to choose more vertically elongated stimuli as "the perfect circle", since cylinder lenses that correct for with-the-rule astigmatism vertically compress images.

The results, shown in the lower portion of Figure 21, indicated that there was a significant interaction between group and wear ($F(1,65)=9.66$, $p=0.003$). Post-hoc comparisons indicated mean responses for the control group did not differ between the glasses-on and glasses-off condition. In contrast, the astigmatism group did significantly differ between glasses-on and glasses-off conditions, such that the children tended to choose more vertically elongated stimuli in the glasses-on condition as predicted.

2.3.3 Outcome Measures: Plasticity over 1 Month and 1 Year

Analyses in this section focus on evaluating change in vision from baseline to 1 month and from baseline to 1 year for the astigmatism groups in comparison to the control group. This section provides details of the results of statistical analyses. A general summary and interpretation is provided at the end of the Results Section.

Group by time repeated measures ANOVAs were conducted, and the reports that follow focus on the significance of the interaction between group and time. Main effects of group are not of primary interest, as differences among groups were reported at baseline. In addition, main effects of time are of limited interest for the purpose of this report because main effects of time, without significant interactions between time and group, would simply indicate that there were improvements across groups due to visual development or, more likely in the case of 1 month data, improvements due to practice effects. Developmental effects were evaluated in previous analyses.

Summaries of analyses are provided in Table 6 for 1 month data and Table 7 for 1 year data. In addition, Figures 22-26 plot mean change for each measure from baseline to 1 month, and from baseline to 1 year.

Recognition (Letter) Acuity. Both the myopic/mixed and hyperopic groups had significantly poorer mean acuity than the control group at baseline. To determine if there was improvement with 1 month of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 month) repeated measures ANOVA on letter acuity data was conducted. The results indicated that there was no significant interaction between group and time: the amount of change that occurred from baseline to 1 month did not differ across groups.

A group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 year) repeated measures ANOVA on letter acuity data was conducted to determine if there were improvements with 1 year of glasses wear. The results indicated that there was no significant interaction between group and time: the amount of change that occurred from baseline to 1 year did not differ across groups.

Resolution (Grating) Acuity. Baseline analyses indicated that the myopic/mixed group had significantly poorer grating acuity for vertical, horizontal and oblique lines, in comparison to the control group, and the hyperopic group had significantly poorer grating acuity for oblique lines, in comparison to the control group. Vertical and horizontal grating acuity for the hyperopic group in comparison to the control group approached but did not reach significance. To determine if there was improvement with 1 month of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 month)

Table 6. One Month Data Analysis Summary Table. All analyses conducted with age as a covariate to control for age (i.e., developmental differences) across groups. Sample sizes for the control, myopic/mixed, and hyperopic groups, respectively, provided in parenthesis.

Measure (Sample Sizes)		3 Groups ANOVAs Group x Time Interaction		Post-Hoc Tests: Group x Time Interactions: Control vs. Myopic/ Mixed	Control vs. Hyperopic	Myopic/ Mixed vs. Hyperopic
Letter Acuity (91,28,19)		NS (0.27)				
Grating Acuity (91,28,17)	V	Group x Orient. x time NS	V NS			
	H		H NS			
	O		O NS			
	V-H					
Vernier Acuity (89,26,17)	V	Group x Orient. x Time NS	V NS			
	H		H NS			
	O		O NS			
	V-H					
Contrast Sensitivity 1.5 cy/deg	V	Group x Orient. x Time NS				
	H					
	V-H					
Contrast Sensitivity 6.0 cy/deg	V	Group x Orient. x Time NS				
	H					
	V-H					
Contrast Sensitivity 18.0 cy/deg	V	Group x Orient. x Time NS	V NS			
	H		H * (0.05)	* (0.048)	NS (0.073)	NS (0.64)
	V-H					
Stereoacuity (92,28,18)		* (=0.015)		NS (0.61)	* (=0.007)	NS (=0.07)

* Statistically significant before Bonferroni correction applied (p values represent uncorrected significance level). V = Vertical Stimuli, H = Horizontal Stimuli, O = Oblique Stimuli, V-H = Vertical – Horizontal, NS = not statistically significant.

Table 7. One Year Data Analysis Summary Table. All analyses conducted with age as a covariate to control for age (i.e., developmental differences) across groups. Sample sizes for the control, myopic/mixed, and hyperopic groups, respectively, provided in parenthesis.

Measure (Sample Sizes)		3 Groups ANOVAs Group x Time Interaction		Post-Hoc Tests: Group x Time Interactions: Control vs. Myopic/ Mixed	Control vs. Hyperopic	Myopic/ Mixed vs. Hyperopic
Letter Acuity (56,17,9)		NS (=0.52)				
Grating Acuity (55,17,8)	V	Group x Orient. x Time NS	V NS H NS O NS			
	H					
	O					
	V-H					
Vernier Acuity (54,16,9)	V	Group x Orient. x Time NS	V NS H NS O NS			
	H					
	O					
	V-H					
Contrast Sensitivity 1.5 cy/deg	V	Group x Orient. x Time NS	V NS H * (0.013)			
	H			NS (0.97)	* (0.006)	* (0.028)
	V-H					
Contrast Sensitivity 6.0 cy/deg	V	Group x Orient. x Time NS	V NS H * (0.012)			
	H			NS (0.77)	* (0.005)	* (0.026)
	V-H					
Contrast Sensitivity 18.0 cy/deg	V	Group x Orient. x Time NS	V NS H NS			
	H					
	V-H					
Stereoacuity (57,17,9)		* (p=0.017)		NS (0.85)	* (0.005)	NS (0.14)

* Statistically significant before Bonferroni correction applied (p values represent uncorrected significance level). V = Vertical Stimuli, H = Horizontal Stimuli, O = Oblique Stimuli, V-H = Vertical – Horizontal, NS = not statistically significant.

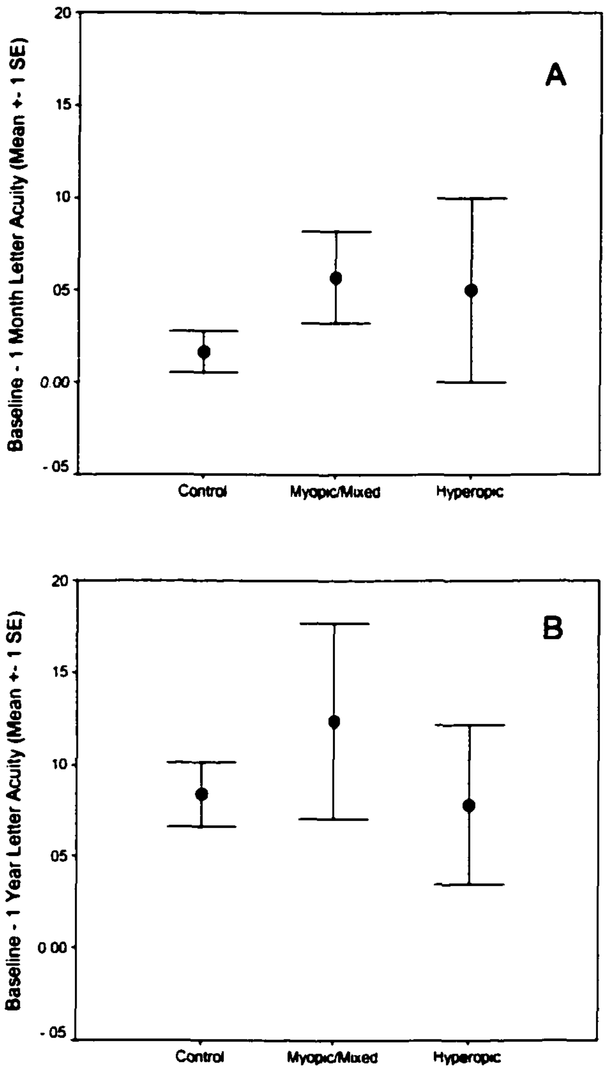


Figure 22. Mean change in recognition (letter) acuity by group. Mean +/- 1 standard error of differences between baseline and 1 month follow-up measures are shown in A, and mean +/- 1 standard error of differences between baseline and 1 year follow-up measures are shown in B.

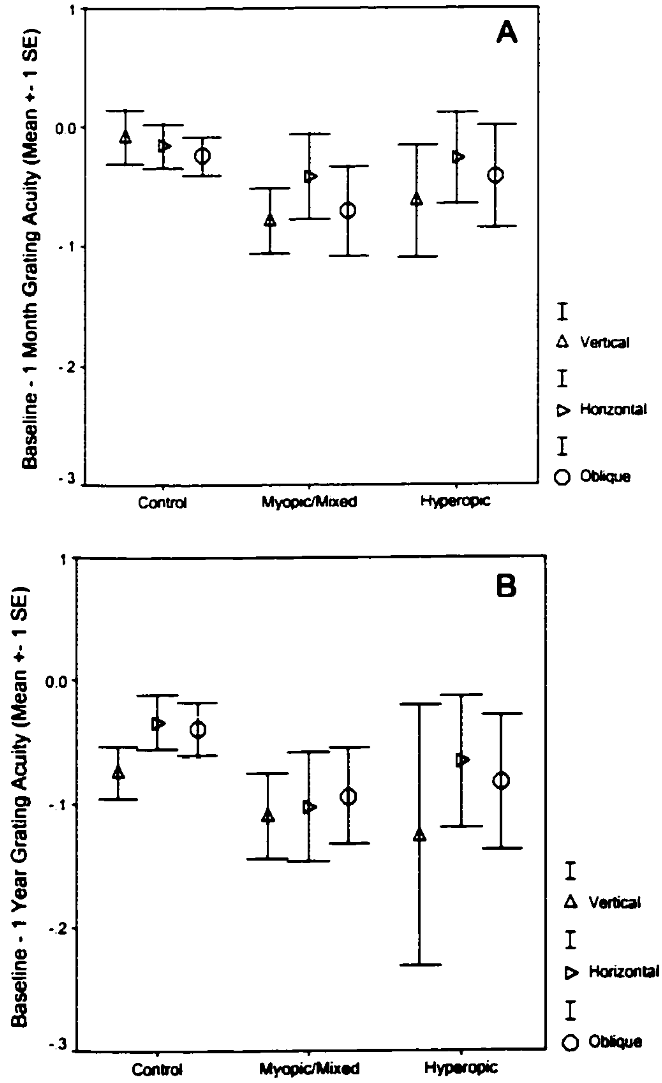


Figure 23. Mean change in resolution (grating) acuity by group. Mean +/- 1 standard error of differences between baseline and 1 month follow-up measures are shown in A, and mean +/- 1 standard error of differences between baseline and 1 year follow-up measures are shown in B.

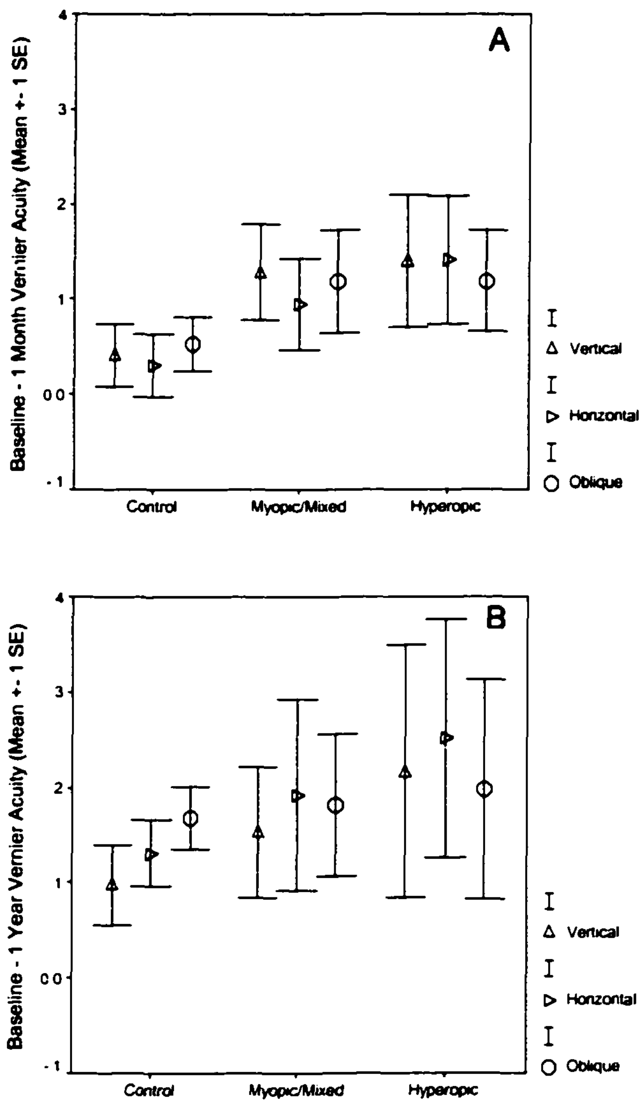


Figure 24. Mean change in vernier acuity by group. Mean +/- 1 standard error of differences between baseline and 1 month follow-up measures are shown in A, and mean +/- 1 standard error of differences between baseline and 1 year follow-up measures are shown in B.

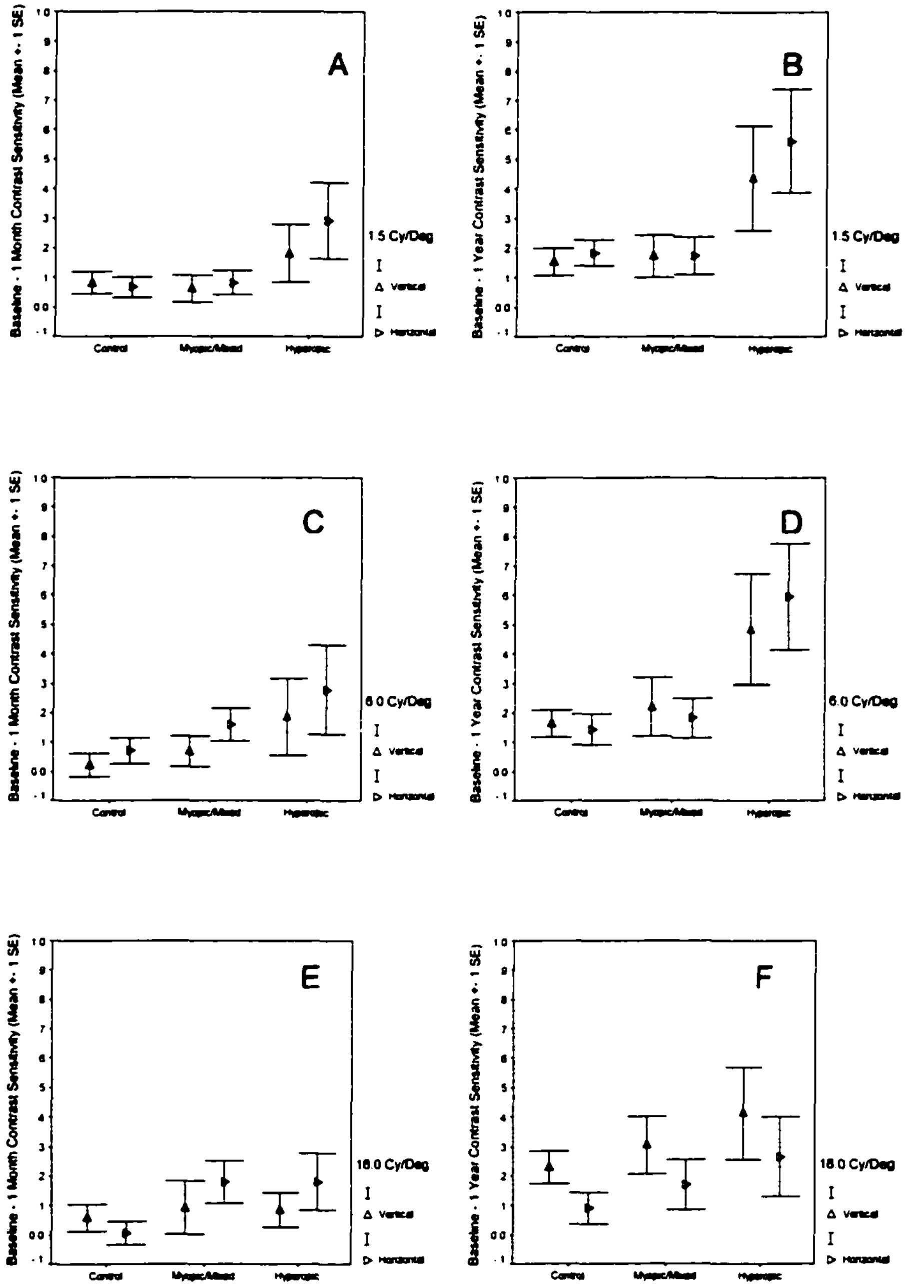


Figure 25. Mean change in contrast sensitivity by group. Mean +/- 1 standard error of differences between baseline and follow-up measures are shown in A and B for low spatial frequency stimuli, C and D for middle spatial frequency stimuli, and E and F for high spatial frequency stimuli. Change from baseline to 1 month are plotted in A, C, and E, and change from baseline to 1 year are shown in B, D, and F.

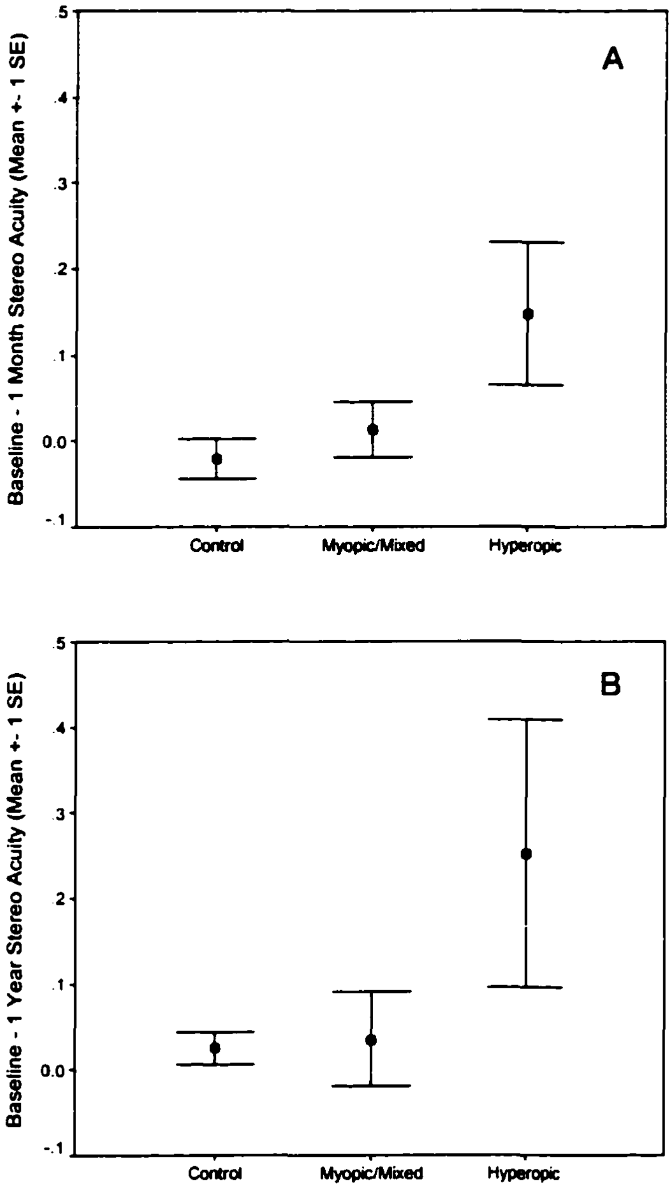


Figure 26. Mean change in stereoacuity by group. Mean +/- 1 standard error of differences between baseline and 1 month follow-up measures are shown in A, and mean +/- 1 standard error of differences between baseline and 1 year follow-up measures are shown in B.

repeated measures ANOVA on grating acuity data for each stimulus orientation was conducted. The results of the analyses yielded no significant interactions between group and time, indicating that there were no differences in the amount of change observed from baseline to 1 month across groups.

To determine if there was improvement with 1 year of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 year) repeated measures ANOVA on grating acuity data for each stimulus orientation was conducted. The results of the analyses yielded no significant interactions between group and time, indicating that there were no differences in the amount of change observed from baseline to 1 year across groups.

Vernier acuity. Baseline measures indicated that mean horizontal, vertical and oblique vernier acuity for the myopic/mixed group and for the hyperopic group were significantly poorer than the control group. To determine if there was improvement with 1 month of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 month) repeated measures ANOVA on vernier acuity data for each stimulus orientation was conducted. The results of the analyses yielded no significant interactions between group and time, indicating that there were no differences in the amount of change observed from baseline to 1 month across groups.

To determine if there was improvement with 1 year of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 year) repeated measures ANOVA on vernier acuity data for each stimulus orientation was conducted. The results of the analyses yielded no significant interactions between group and time, indicating that there were no differences in the amount of change observed from baseline to 1 year across groups.

Contrast Sensitivity. Group by time ANOVAs were conducted on 1.5, 6.0, and 18.0 cy/deg contrast sensitivity for horizontal and vertical stimuli to determine if there were improvements from baseline to 1 month. The analyses yielded no significant interactions (group x time) for 1.5 and 6.0 cy/deg contrast sensitivity for horizontal or vertical stimuli, and no significant interaction for 18 cy/deg contrast sensitivity for vertical stimuli. However, the interaction was marginally significant for 18 cy/deg contrast sensitivity for horizontal stimuli ($F(2,131)=3.06$, $p=0.05$). Post-hoc analyses indicated that there was greater improvement for the myopic/mixed group in comparison to the control group, although this effect did not reach significance after correction for multiple comparisons. The difference between the hyperopic group and the control group did not reach significance.

Group by time ANOVAs were also conducted on 1.5, 6.0, and 18.0 cy/deg contrast sensitivity for horizontal and vertical stimuli to determine if there were any significant improvements from baseline to 1 year. The analyses yielded no significant interactions (group x time) for vertical stimuli at any of the three spatial frequencies. However, the interaction was significant for horizontal stimuli at 1.5 ($F(2,76)=4.63$, $p < 0.02$) and 6 cy/deg ($F(2,76)=4.73$, $p = 0.02$), but not at 18 cy/deg. Post-hoc analyses indicated that for both 1.5 and 6.0 cy/deg horizontal stimuli, there was significantly greater improvement for the hyperopic group, but not the myopic/mixed group, in comparison to the control group. Comparisons between the hyperopic and myopic/mixed group were significant before, but not after correction for multiple comparison.

Stereoacuity. At baseline, the hyperopic group had significantly poorer mean stereoacuity than the control and myopic/mixed groups. To determine if there was improvement with 1 month of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 month) repeated measures ANOVA on stereoacuity data was conducted, and the analysis yielded a significant interaction ($F(2,133)=4.37$, $p < 0.02$). Post-hoc analyses indicated that there was significantly greater improvement from baseline to 1 month for the hyperopic group in comparison to the control group. The amount of change in the myopic/mixed group did not differ from that observed in the control group or the hyperopic group.

To determine if there was improvement with 1 year of glasses wear, a group (control, myopic/mixed, hyperopic) by time (baseline vs. 1 year repeated measures ANOVA on stereoacuity data was conducted, and the analysis yielded a significant interaction ($F(2,80) = 4.3$, $p< 0.02$). Post-hoc analyses indicated that there was significantly greater improvement from baseline to 1 year for the hyperopic group in comparison to the control group. The amount of change in the myopic/mixed group did not differ from that observed in the control group or the hyperopic groups.

Form Adaptation. Mean scores for each wear (glasses on/glasses off) x time (baseline/1 month) condition were determined by averaging responses on four trials: two trials each for the outline circle and checkered circle stimuli, one on which the child started the task on the –12 stimulus, and one on which the child started the task on the

+12 stimulus. As previously noted, raw data ranged from −12 to +12 in whole numbers, with negative numbers representing vertically compressed circles, 0 representing a true circle, and positive numbers representing vertically elongated circles

Since analysis of baseline data did suggest that the eyeglasses do induce distorted perception for the astigmatism group, analyses were aimed at determining if subjects in the astigmatism group adapted to the distortion after 1 month of wear. Figure 21 illustrates the predicted pattern of results and the observed pattern of results. Adaptation was determined both in terms of reduction of effect, based on changes in perception when glasses were on, and in terms of negative aftereffects, based on changes in perception when glasses were off. Separate repeated measures ANOVAs were conducted on data obtained when glasses were on, and data obtained when glasses were off. The analyses yielded no main effect of time, and no significant interactions between group (control vs. astigmatism) and time (baseline vs. 1 month), indicating that there was no difference between groups in the pattern of form perception measures at baseline vs. follow-up.

2.3.4 General Summary and Interpretation of Results

Baseline Data Analyses: Normal Development in 5- to 14-year-olds. Results suggest that, with the exception of stereoacuity, significant development in basic perceptual functions occurs in the 5- to 14-year-old age range. Recognition acuity, resolution acuity, vernier acuity, and contrast sensitivity were significantly correlated with age, and the correlation between age and stereoacuity approached significance. Closer examination of change across age groups revealed differences in patterns of development across perceptual measures. Developmental data revealed that recognition acuity in this age range develops significantly between 7/8 year-old and 9/10 year-old age groups. Grating acuity develops gradually between age 7/8 year-old and 11- to 14-year-old age groups, and vernier acuity develops gradually between 5/6 year-old and 11- to 14-year-old age groups. Contrast sensitivity, like resolution acuity, appears to develop notably between the 7/8 year-old and 9/10 year-old age groups, as difference between these groups reached or approached significance for low, middle, and high spatial frequency stimuli.

Baseline Data Analyses: Effects of Deprivation and Spatial Distortion on Perception. Results of analyses suggested that astigmatism-related deprivation had significant effects on development of all measures of perception studied here, and that wear of cylinder lenses resulted in measurable distortion in form perception.

Recognition (Letter) Acuity. Both myopic/mixed and hyperopic astigmatism groups had significant deficits for resolution acuity (in comparison to the control group). These results were as predicted, and suggest that astigmatism-related deprivation results in deficits in recognition acuity.

Resolution (Grating) Acuity. The myopic/mixed group had significant deficits for perception of horizontal, vertical and oblique grating acuity stimuli, and showed greater deficits for horizontal than for vertical stimuli (this effect approached but did not reach significance). The hyperopic group showed significant deficits for perception of oblique grating acuity stimuli, showed deficits for perception of horizontal and vertical stimuli that neared significance, and showed no evidence of orientation dependent (horizontal vs. vertical) differences in resolution acuity deficits. These data were as predicted patterns for the myopic/mixed group: there appeared to be greater perceptual deficits for the stimulus orientation for which subjects experienced greatest deprivation, i.e., horizontal stimuli. Data from the hyperopic group were not quite as predicted, and show essentially equivalent deficits across stimulus orientation. Predictions were that there would be greater deficits for vertical than for horizontal stimuli, since these subjects presumably experienced greater deprivation for vertical stimuli.

Vernier Acuity. Both myopic/mixed and hyperopic astigmatism groups had significant deficits for perception of horizontal, vertical and oblique vernier acuity stimuli, although no orientation differences (horizontal vs. vertical) in perceptual deficits were observed in either astigmatism group. Patterns of deficits across stimulus orientation were not as predicted for either the myopic/mixed astigmatism group, in which it was predicted that there would be greater deficits for perception of horizontal stimuli, nor for the hyperopic astigmatism group, in which it was predicted that there would be greater deficits for perception of vertical stimuli.

Contrast Sensitivity. For low spatial frequency contrast sensitivity, the myopic/mixed group demonstrated no significant deficits, while the hyperopic group showed significant deficits for only horizontal stimuli, and a marginally significant difference in perception of horizontal and vertical stimuli. For the hyperopic group, these results were the opposite of the predicted pattern of results: it was expected that perception of vertical stimuli would be poorer than for horizontal stimuli. These results also did not support the prediction that myopic/mixed astigmats would show poorer perception for horizontal than vertical stimuli.

For middle spatial frequency contrast sensitivity, both the myopic/mixed and hyperopic astigmatism groups showed significant deficits for perception of both horizontal and vertical stimuli, and no difference between perception across stimulus orientation. These results suggest that astigmatism-related deprivation influences perception of middle range spatial frequency stimuli, but they do not support the prediction that myopic/mixed astigmats would show poorer perception for horizontal stimuli, and hyperopic astigmats would show poorer perception for vertical stimuli.

For high spatial frequency stimuli, both the myopic/mixed and hyperopic astigmatism groups showed significant deficits for perception of horizontal and vertical stimuli, and the myopic/mixed group showed greater deficits for the horizontal stimuli than for vertical stimuli. These results suggest that astigmatism-related deprivation influences perception of high spatial frequency contrast sensitivity, and support the prediction that myopic/mixed astigmats would show poorer perception for horizontal than for vertical stimuli. However, the data did not lend support to the prediction that hyperopic astigmats would show demonstrated poorer perception for vertical than for horizontal stimuli.

Stereoacuity. Deficits for stereoacuity were significant for the hyperopic group, and approached but did not reach significance for the myopic/mixed group. These results suggest that astigmatism-related deprivation influences stereoacuity in hyperopic astigmats, but not myopic/mixed astigmats.

Form Perception. Comparisons in baseline form perception measures indicated mean responses for the control group did not differ between the glasses-on and glasses-off condition. In contrast, the astigmatism group did significantly differ between glasses-on and glasses-off conditions, such that the children tended to choose more vertically elongated stimuli in the glasses-on condition. In general, this pattern is consistent with what was predicted, and suggests that this task is in fact measuring the distortion experienced when the cylinder lenses are worn by the children in the astigmatism group. However, one aspect of the pattern of the results is not consistent with the original prediction: I predicted that the children in the astigmatism group would not differ from the control group when they *were not* wearing their glasses, but they would differ from the control group when they *were* wearing their glasses. However, the results yielded the opposite pattern of results: the astigmatism group did not differ from the control group when they *were* wearing their glasses, but differed from the control group when they *were not* wearing their glasses. These results suggests that the children in the astigmatism group perceive the circles differently than the control group when they are not wearing their glasses, i.e., the perceive vertically reduced ovals as more circular, in comparison to the control group who reported that stimuli close to real circles were most circle-like. However, as previously noted, data from the astigmatism group did show the glasses do result in changes in form perception in the direction predicted by the distortion induced by the cylinder lenses.

Outcome Analyses: Plasticity over 1 month and 1 year. The data revealed little evidence for plasticity with regard to recovery from the effects of astigmatism-related deprivation. After 1 month, there was evidence for significant improvement only for stereoacuity in the hyperopic astigmatism group. After 1 year, there was evidence of significant improvement in perception of low and middle range spatial frequency contrast sensitivity for horizontal stimuli in the hyperopic astigmatism group, and significant improvement in stereoacuity for the hyperopic group. Improvement in contrast sensitivity for horizontal stimuli is an unexpected result, as ware baseline findings that indicated that the hyperopic group demonstrated significant deficits for perception of horizontal contrast sensitivity stimuli: predictions suggested that there would be greater deficits for vertical than for horizontal stimuli in this group.

The results indicated that there was no difference among groups in the pattern of form perception at baseline vs. 1 month follow-up across the astigmatism and control groups. Thus, these data do not provide any indication that the subjects in the astigmatism group adapted to the distortion induced by the cylinder lenses.

3. DISCUSSION

The study presented here offers several contributions to the literature on visual development, deprivation, recovery from deprivation, and perceptual adaptation. Baseline analyses provide a comparison of recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity development in between the ages of 5 to 14 years, and a large-sample description of the effects of astigmatism-related deprivation on visual development in children. Primary outcome measures provided a prospective analysis of plasticity with regard to recovery from the effects of astigmatism-related visual deficits in children and adaptation to spatial distortion in children. In what follows, I discuss the findings related to each of these aspects of the present study in greater detail.

3.1 Normal Visual Development in Grade-School Children

Analysis of baseline data in for non-astigmatic children provided evidence for development in several basic perceptual functions between ages 5 and 14 years. Developmental analyses suggested that there was a significant relation between age and visual performance on all measures, with the exception of stereoacuity, which approached but did not reach significance. These results indicate that letter acuity, grating acuity, vernier acuity, and contrast sensitivity continue to develop in this age range.

Analyses aimed at narrowing down the grade-school age range during which most development occurs for each perceptual function yielded consistent results for letter acuity and contrast sensitivity: most development occurred between ages 7 and 10. Grating acuity also appeared to have a period of greater development starting around age 7, and continuing to age 11-14. In contrast, vernier acuity appeared to develop more gradually across the 5- to 14- year age range, and stereoacuity appeared to develop slowly between 5 and 10 years. Unfortunately, these data can not tell us if subjects reached adult levels, as adult subjects were not included in the present study.

It is interesting that for several measures, i.e., letter acuity, grating acuity, and contrast sensitivity, the age range from 7 to 10 seems to be associated with marked improvements. These data can not provide clear answers as to why development increases after a relatively slow period between age 5 and 7. However, one possibility is that the type of visual experience children are exposed to at different ages may influence these developmental patterns. For example, as children make their way through grade school, it is likely that they spend increasing amounts of time doing near work that requires good vision for detail, e.g., letters and numbers. Perhaps this experience provides a type of discrimination learning, where vision improves as a result of "practice" in discriminating fine perceptual stimuli. The early slow period of grade-school visual development, age 5 to 7 years, includes the kindergarten and first grade years, during which children are first learning to read, but tend to do so with large letter stimuli. The rapid period of development, age 7 to 9 years, include second and third grade, when children are becoming more adept at reading, and are spending more time reading with relatively smaller letter stimuli. Thus, the general pattern of results obtained here are at least consistent with an experiential effect on patterns of visual development.

Freeman (1978) reported some interesting findings regarding configurational differences in visual acuity that may be related to the developmental patterns observed here, and may provide an example of how typical visual experience beyond early childhood can lead to discrimination learning. Freeman reported differences in letter visual acuity based on the configuration of the test display: visual acuity was significantly better for letters presented in rows than for letters presented in columns. In addition, he provided experimental evidence to support the hypothesis that these acuity differences are experience dependent. First, he reported that orientation differences were not obtained for non-letter acuity stimuli (Landolt C). Second, native Chinese readers demonstrated no such acuity difference for Chinese characters read in rows vs. columns, a finding that is particularly significant to the experience-dependent hypothesis because Chinese is printed and read in either rows or columns. Finally, young children who could identify letters but not yet read also failed to demonstrate acuity differences for letters presented in rows vs. columns. Freeman suggested that these data provide evidence that specific visual experiences, particularly reading, influence visual resolution. I believe these data provide further support for the hypothesis that patterns of development in grade-school reflect the influence of visual experience during this period of development.

While the goal of these developmental analyses was to better understand the development of visual perception, it is important to note that another possible interpretation of any age effects is that older children tend to perform better on the tasks due to attentional or motivational factors, or may have more liberal criteria for responding in these detection tasks once they approach threshold. Significant attempts were made to reduce the cognitive demands of the tasks used for assessment and to engage the children in the task, and thus the likelihood that this alternative explanation can account for the developmental effects observed here is reduced, but can not be completely ruled out.

Overall, these data indicate that some development of these visual functions still occurs in this age range. Furthermore, the patterns of development indicate that visual experiences, such as reading, may influence development during this age range, suggesting the use of discrimination learning strategies during this age range may have notable effects on development, and perhaps may be useful in the treatment of developmental visual disorders, such as recovery from the effects of early visual deprivation. This possibility will be discusses further in the following sections.

3.2 Effects of Astigmatism-Related Deprivation on Visual Development

Baseline comparisons between astigmatism and control groups contributed important data on the extent to which various visual perceptual functions are influenced by the presence of high astigmatism during development. Vision was measured under conditions in which each child wore his or her best optical correction. Thus, any deficits detected could not be attributed to optical effects, and therefore must originate from higher levels of the visual system.

Baseline analyses indicated that the presence of astigmatism during development was associated with reduced perceptual capabilities on all measures of visual function reported here: recognition acuity, resolution acuity, vernier acuity, contrast sensitivity, and stereoacuity. In what follows, I discuss the implications of these findings in the context of previous research, and potential for further research.

Letter acuity was significantly reduced for both the myopic/mixed and hyperopic astigmatism groups. In the control group, mean acuity was approximately 20/20, whereas mean acuity in the astigmatism groups was approximately 20/32. Because letter acuity requires fine resolution acuity in addition to the ability to identify fine letter stimuli, it is not clear if reduced letter acuity is associated only with deficits in resolution acuity, or if it may also be associated with deficits in higher level form perception. Previous research has indicated that other forms of amblyopia are associated with higher level perceptual deficits including form perception even when stimuli are presented above resolution acuity limits (Hess, Campbell, and Greenhalgh, 1978, Hess, Wang, Demanins, Wilkinson, and Wilson, 1999, Lewis, Ellemberg, Maurer, Wilkinson, Wilson, Dirks, and Brent, 2002). Research is currently is progress to determine if astigmatism-related deprivation results in deficits in perception of global form.

Grating acuity results indicated that the myopic/mixed group showed greater deficits for horizontal than for vertical stimuli. These results are consistent with data from adults indicating orientation-dependent deprivation can result in reduced visual/perceptual capabilities for stimuli of the deprived orientation (Freeman, Mitchell, and Millodot, 1972, Mitchell, Freeman, Millodot, and Haegerstrom, 1973). Uncorrected myopic/mixed with-the-rule astigmats experience greater defocus for horizontal lines than for vertical lines when viewed at distance (see Figure 2d-f), and these data indicate that reduced vision persists even after the optical cause for reduced vision, astigmatism, is corrected. Dobson et al. (2002) reported the same pattern of results for preschoolers with myopic/mixed astigmatism.

Grating acuity results for the hyperopic astigmatism group indicated that these children have equally reduced acuity for stimuli across orientations. I should note, however, that deficits for horizontal and vertical stimuli did not reach statistical significance. The smaller sample size and greater variability (possibly due to younger mean age) in this group resulted in lower statistical power, and is likely to have been an important reason that statistical significance was not reached. However, this pattern of results is consistent with the results of Dobson et al. (2002), who reported equally reduced acuity for horizontal and vertical stimuli in preschoolers with hyperopic with-the-rule astigmatism. Mitchell et al., (1973), however, predicted and reported reduced acuity for stimuli corresponding to the more hyperopic focus (vertical, in the case of our sample) in hyperopic astigmats, reasoning that uncorrected hyperopic astigmats would be likely to accommodate to focus the nearer focal point (horizontal, in the case of our subjects), and thus would experience greater deprivation for vertical stimuli. Freeman (1975) provided support for this prediction when he reported that measurements of accommodation in a subject with hyperopic astigmatism indicated that he accommodated to focus stimuli at the least hyperopic meridian. However, the results presented here, and those reported by Dobson et al. (2002) suggest that hyperopic astigmatic children do not accommodate in the manner that Mitchell et al. predicted for hyperopic astigmats. The observed reduced acuity across orientations suggests that these children, when uncorrected, may accommodate someplace between the anterior and posterior focal points, or may fluctuate accommodation, thus resulting in visual experience that does not provide them with consistently clear input for stimuli of any orientation (Dobson et al., 2002). We are currently conducting a study to determine where hyperopic astigmats focus for distant and near targets when astigmatism is uncorrected. This research should provide us with better understanding of the nature of the visual experience of uncorrected hyperopic astigmats, and the resulting visual/perceptual deficits reported here.

Vernier acuity was significantly reduced for stimuli of all three orientations for both the myopic/mixed and hyperopic astigmatism groups. These data suggest that astigmatic defocus induces deficits in perception of fine spatial relationships. It is not clear why deficits for vernier acuity were not dependent upon stimulus orientation. Perhaps resolution of vertical and horizontal vernier acuity stimuli require clear perception of both horizontal and vertical stimulus information because while the overall stimulus is one orientation (e.g., horizontal), the offset to be detected is the orthogonal orientation (vertical). However, previous studies have reported orientation dependent deficits in subjects with high astigmatism (Mitchell et al., 1973, Gwiazda et al., 1986).

Contrast sensitivity deficits for astigmatic subjects varied across spatial frequencies. For low spatial frequency stimuli (1.5 cy/deg), deficits were apparent only for the hyperopic astigmatism group, and only for horizontal stimuli. For middle and high spatial frequency stimuli, both astigmatism groups had significant deficits for perception of both horizontal and vertical stimuli, and for high spatial frequency stimuli, the myopic/mixed group showed significantly greater deficits for horizontal than for vertical stimuli. Thus, the results for high spatial frequency contrast sensitivity mirrored the grating acuity results for the myopic/mixed group, providing further evidence that the deprivation was greater for the more myopic stimulus orientation (horizontal). It is not clear why there were deficits for low spatial frequency horizontal stimuli for the hyperopic group but high and middle range contrast sensitivities were poor for both horizontal and vertical stimuli, further suggesting that hyperopic astigmats may not habitually bring the more anterior focal line (horizontal stimuli) into focus through accommodation.

In general, the contrast sensitivity results provide us with a greater understanding of the how deficits associated with astigmatism-related deprivation may influence perception in real-world circumstances. The fact that deficits were observed for high spatial frequency stimuli is not surprising given the reduced recognition and resolution acuity in astigmatic subjects – the astigmatic children clearly have difficulty perceiving fine visual detail even with the appropriate optical correction. However, deficits observed for mid range spatial frequency stimuli suggests that visual perceptual deficits may extend beyond fine perceptual tasks, and may influence perception of their general environment to a greater extent than we might have expected based solely on recognition and resolution acuity results. In particular, deficits for both high and mid range spatial frequency information under low contrast conditions are likely to result in difficulty in differentiating much of our visual environment, which includes a significant amount of low contrast visual information.

Stereoacuity was significantly reduced only for the hyperopic group. It is not clear why this group in particular showed such reduced stereoacuity. Children with strabismus are at risk for poor stereoacuity. While strabismus was not detected in any of the children in the hyperopic astigmatism group, children with high hyperopia are at risk for a form of strabismus called accommodative esotropia. Thus, it is possible that some of the children with hyperopic astigmatism may have had mild accommodative esotropia that was not detected at the eye exam, but may have resulted in the small reductions in stereoacuity observed here.

It is not clear if stereo deficits are associated with the spatial distortions induced by the cylinder lenses that correct for the optical effects of astigmatism, or if these are higher level deficits in stereoacuity. Since use of contact lenses to correct astigmatism minimizes spatial distortions induced by the lens curvature, it is possible to evaluate whether stereo deficits are present in the absence of spatial distortion in astigmatic subjects. Unfortunately, due to time and financial constraints, and the fact that putting contact lenses on children would be both invasive and would be significantly complicated in terms of creating a sterile environment within the school setting, this was not evaluated in the present study. However, the present findings of reduced stereoacuity in astigmats provide support for continuing to pursue answers to such questions in further studies.

3.3 Plasticity Associated with Recovery from Effects of Deprivation

The primary question addressed in this study was the extent to which 5- to 14-year-old children demonstrate plasticity with respect to recovery from the effects of astigmatism-related deprivation and with respect to adaptation to spatial distortion. Results regarding recovery from deprivation were generally negative. On average, glasses wear over a 1 month period and over a 1 year period did not result in significant improvements in letter acuity, grating acuity, or vernier acuity. Significant improvements were seen at 1 month and 1 year for the hyperopic group in terms of stereoacuity, although it is not clear if those improvements were due to adaptation to the spatial distortion induced by the lenses, or if they were due to recovery from the effects of visual deprivation on stereoacuity. Some marginally significant improvements were seen for low and mid range spatial frequency contrast sensitivity for horizontal stimuli in the hyperopic astigmatism group. It is important to note that although they were not statistically significant, there were trends towards greater in improvement in the astigmatism groups in comparison to the control group on measures of recognition acuity, resolution acuity, and vernier acuity, suggesting that evidence of plasticity on these measures may have been obtained with greater statistical power (increased sample size, reduced variability).

It is important to note that the conclusion that eyeglass intervention during the 5 to 14 year age range is ineffective in treating this form of amblyopia is only one possible interpretation of the data presented here. In studies aimed at evaluating treatment effectiveness, the issue of subject compliance is always a primary concern. In the study reported here, many efforts were made to encourage compliance in glasses wearing. However, there were some children who were not compliant with treatment, and it is possible that the inclusion of these children weakened treatment effects. Of 23 astigmatic children on whom repeated compliance reports were obtained over the year of eyeglass intervention, only 61% had "very good" or "excellent" compliance. An alternative interpretation of the null treatment effects is that perhaps many of the children had benefited from use of eyeglasses prior to the start of the study. Of the 48 astigmatic children, 35% were wearing eyeglasses when they arrived at the first eye exam. Thus, treatment effects that might have occurred due to eyeglass wear may have already occurred for some subjects, and again may have weakened treatment effects. Finally, it is possible that younger children responded to treatment and older children did not, again weakening treatment effects since data were pooled over a large age range. It would be helpful to compare results for older vs. younger children in this age range to see if there is evidence of plasticity in younger children, but the sample size of astigmatic children in the present study does not allow for meaningful analysis of age effects in treatment effectiveness. However, a larger scale study is currently underway in which recovery from astigmatism-related deprivation in K – 2nd grade children will be compared to recovery from astigmatism-related deprivation in 4th- 6th grade children.

In summary, three factors (compliance, previous treatment, and age effects) may have contributed to the failure to find significant improvement in the children with astigmatism, when viewed as a group. Thus, in is important to interpret the null treatment effects cautiously. In the next section, I look at individual subject data, to determine if there is evidence of treatment effects under conditions in which, theoretically, we would expect them to be strongest.

3.4 Case Studies on Plasticity and Recovery from Effects of Deprivation

The limited sample size in the present study, although greater than previous studies of the effects of plasticity related to recovery from the effects of astigmatism-related deprivation, is not sufficient to conduct sub-analyses based on factors such as compliance, previous eyeglass wear, and treatment age. However, given the potential theoretical and clinical importance of the present study with regard to visual plasticity associated with astigmatism-related deprivation, it seems worthwhile to look at some individual cases to determine if there is any evidence of plasticity related to recovery from astigmatism-related deprivation in this age group.

Since previous treatment and treatment compliance are important variables that could not be statistically controlled for in the present study due to limited sample size, I reviewed the data to determine which astigmatic children did not have a history of previous treatment (glasses wear for full correction of astigmatism) and which children were highly compliant in wearing glasses throughout the 1 year study. I determined that there were just three children who met both of these criteria.

Subject AA: This child was 11 years old when his glasses were first dispensed as part of the present study. He had 8.25 D of mixed astigmatism in the right eye (-5.75 +8.25 x 078) and 7.50 D of mixed astigmatism in the left eye (-5.75 +7.50 x 096). These are unusually high amounts of astigmatism even for a child in this highly astigmatic population. This child did have a history of previous glasses wear, but his eyeglasses only partially corrected his astigmatism (right eye wear was –1.25 +2.62 x 092 at the first eye exam), leaving him with over 5.00 D of uncorrected astigmatism. AA was consistently compliant in wearing his eyeglasses throughout the year.

Subject CJ: This child was 6.6 years old when her eyeglasses were first dispensed as part of the present study. She had 2.75 D of simple myopic astigmatism in the right eye (-2.75 +2.75 x 077) and 3.00 D of mixed astigmatism in the left eye (-2.75 +3.00 x 092). CJ had no history of eyeglass wear, and was compliant with wearing eyeglasses throughout the year, with the exception of a few short periods (days) during which her eyeglasses were broken.

Subject CR: This child was 8.9 years old when her eyeglasses were first dispensed as part of the present study. She had 2.50 D of mixed astigmatism in the right eye (-2.25 +2.50 x 092) and 3.00 D of mixed astigmatism in the left eye (-2.75 +3.00 x 081). CR had no history of previous eyeglass wear, and was compliant with wearing her eyeglasses throughout the study.

Data for each of these three subjects were compared to control group subjects of a similar age, i.e., each subject was compared with mean data from control group subjects who were +/- 1 year of the subject's age in order to generate age-appropriate (developmentally comparable) comparison group for each case study. Data are illustrated in Figure 27 (letter acuity), 28 (grating acuity), 29 (vernier acuity), 30-32 (contrast sensitivity), and 33 (stereoacuity). Review of data overall suggest that at baseline, subject AA demonstrated poor perception in comparison to the control group, but showed

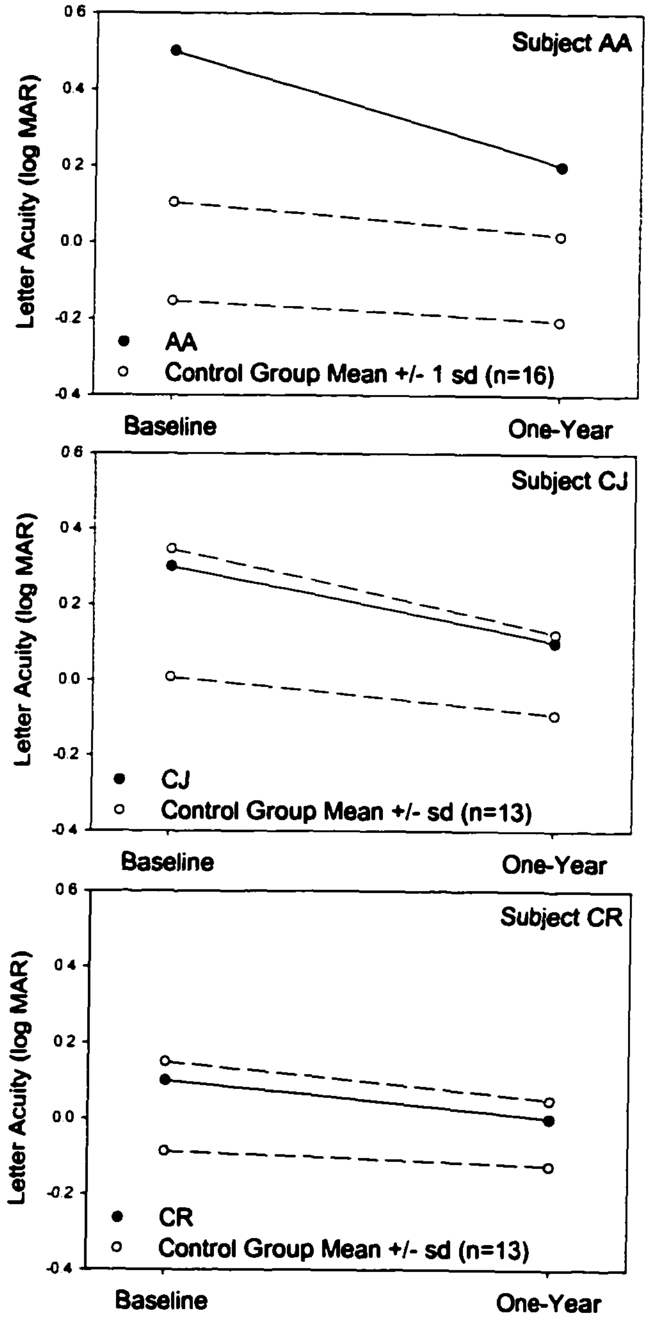


Figure 27. Case studies: Recognition (letter) acuity by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

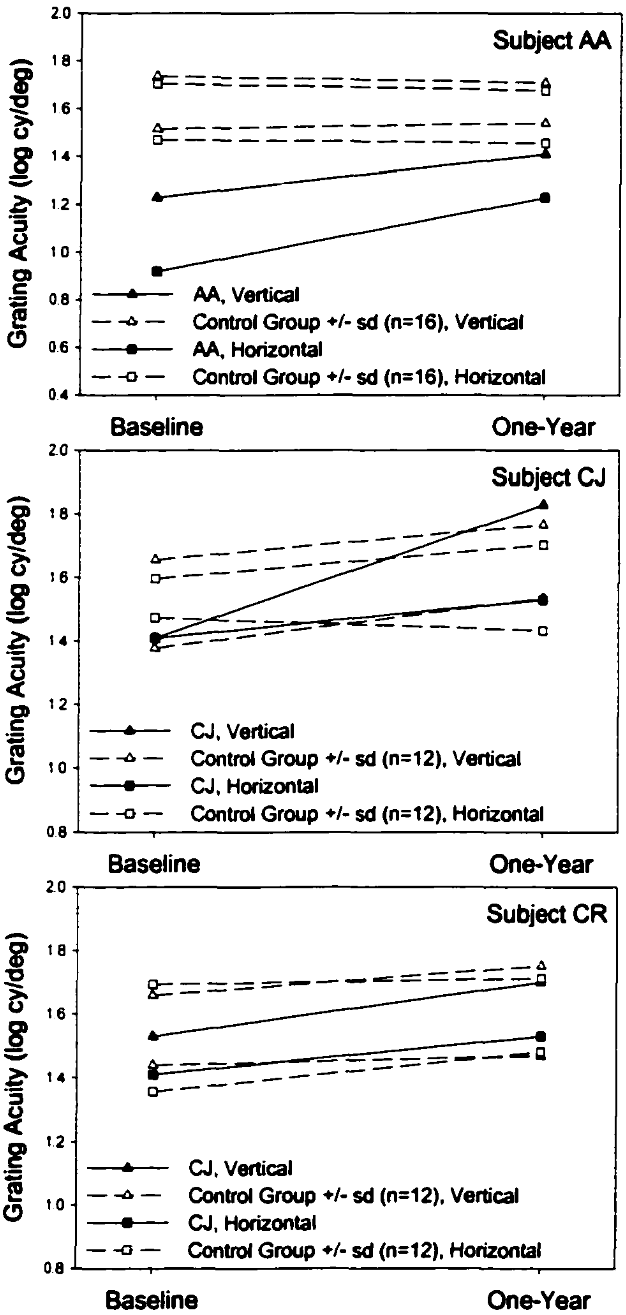


Figure 28. Case studies: Resolution (grating) acuity by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

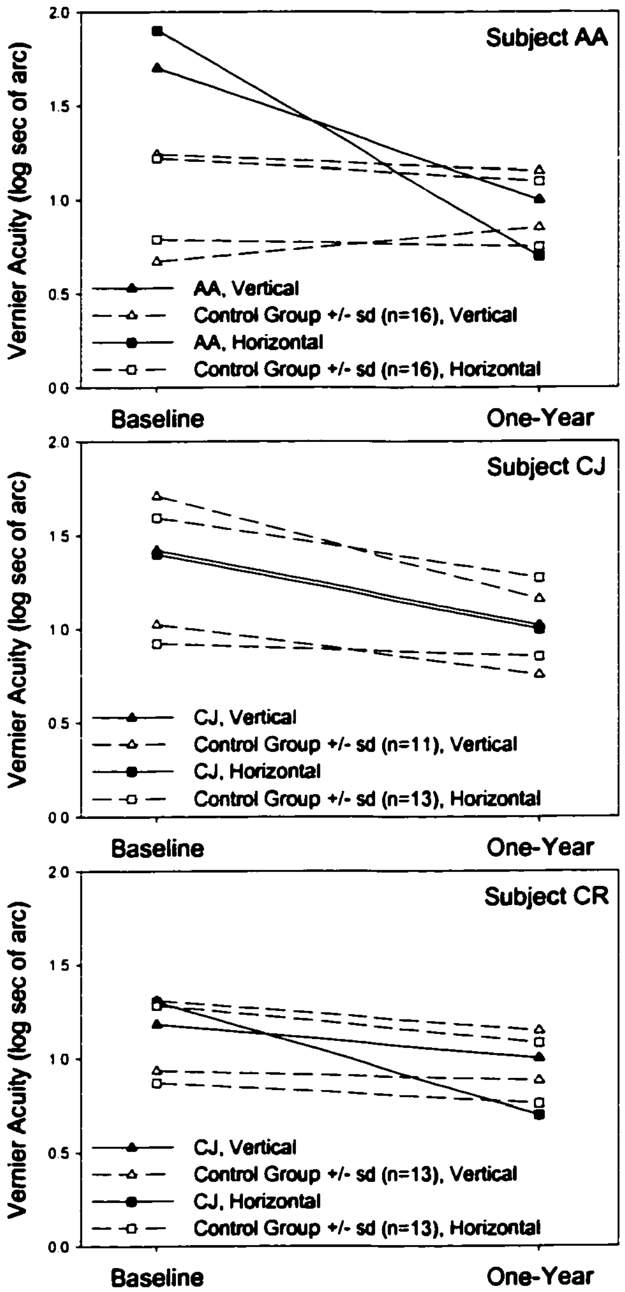


Figure 29. Case studies: Vernier acuity by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

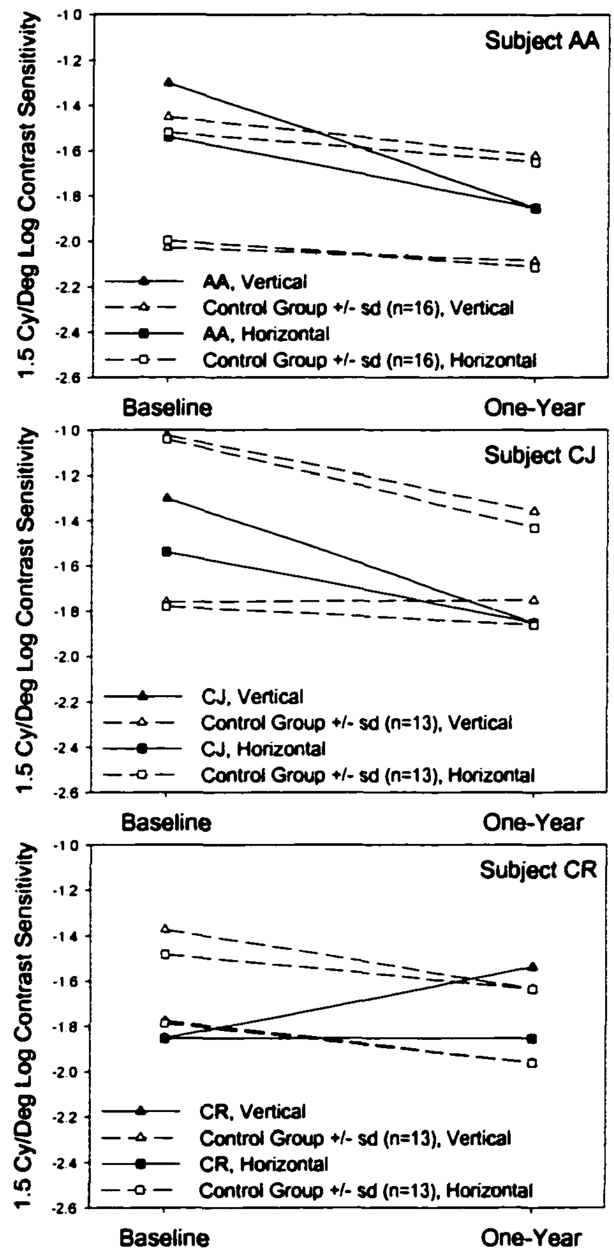


Figure 30. Case studies: Contrast Sensitivity for low spatial frequency stimuli by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

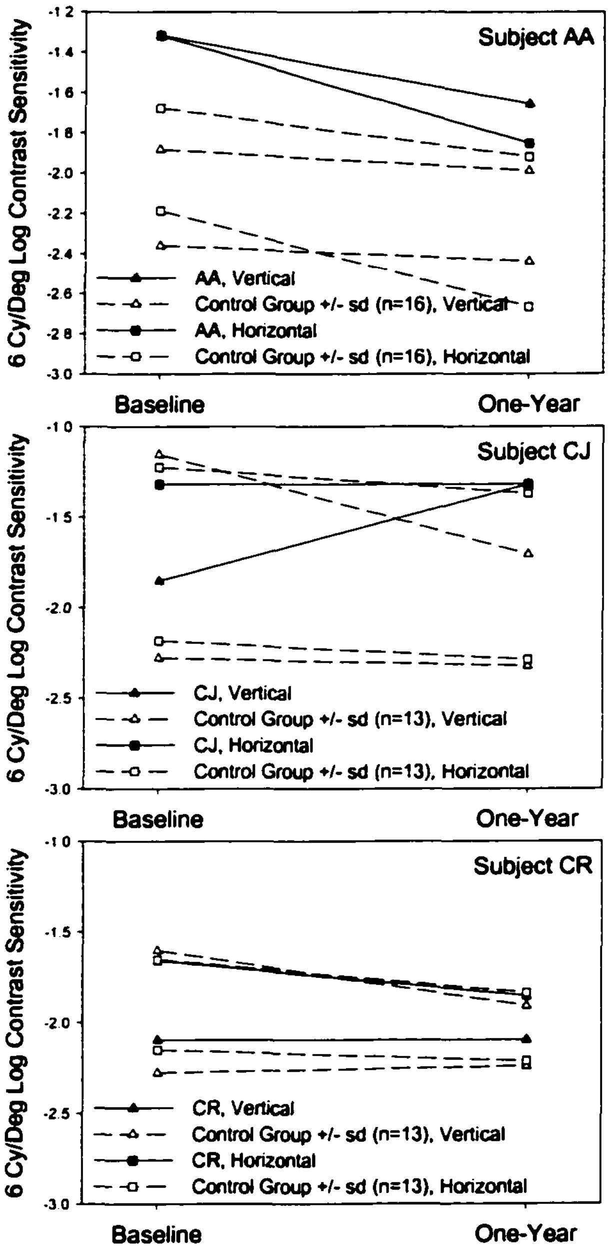


Figure 31. Case studies: Contrast Sensitivity for middle spatial frequency stimuli by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

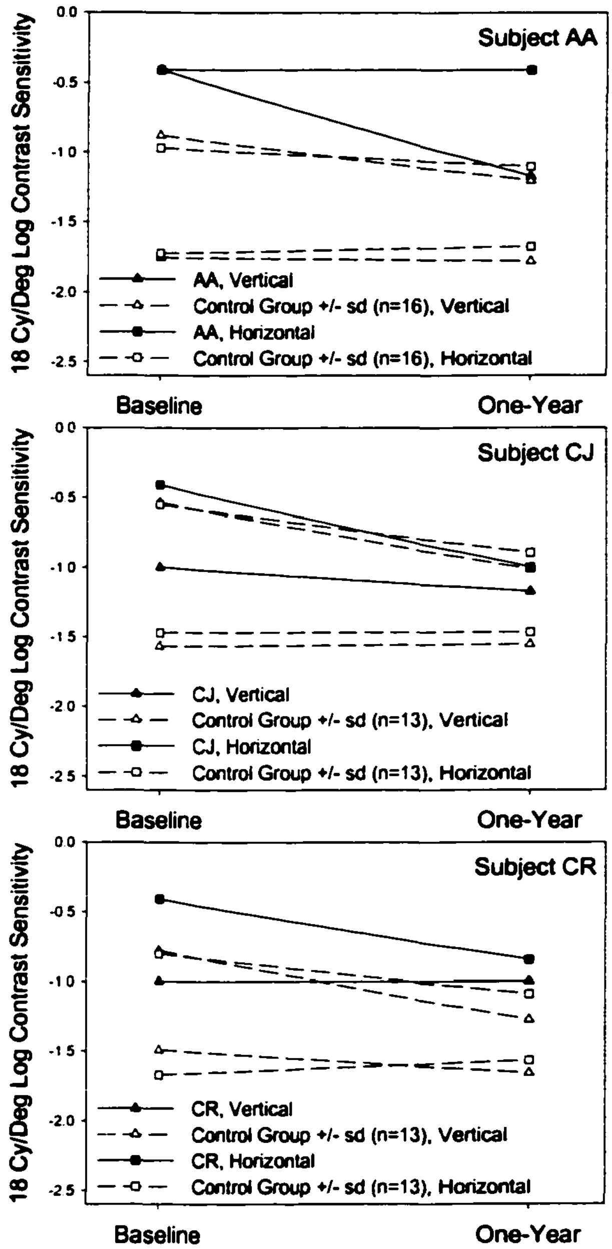


Figure 32. Case studies: Contrast Sensitivity for high spatial frequency stimuli by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

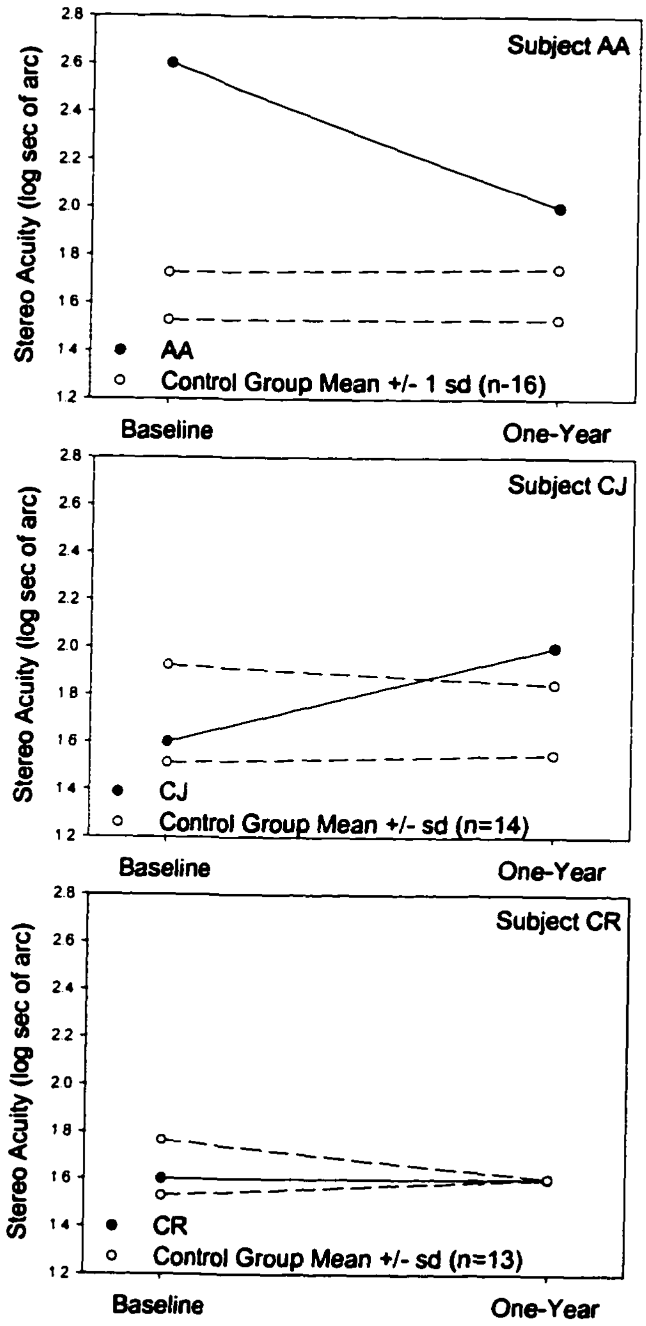


Figure 33. Case studies: Stereoacuity by time. Individual subject data for subjects AA, CJ, and CR plotted with age-matched control group mean + 1 standard deviation and mean – 1 standard deviation.

improvement over the course of the year. Subjects CJ and CR, however, demonstrated perception that was within normal limits for most measures at baseline, and appeared to show improvements similar to that demonstrated by the control group over the course of the year. The failure to find astigmatism-related deficits in these two subjects may be due to the fact they had moderate, rather than severe astigmatism, or perhaps their astigmatism had developed fairly recently, and thus did not result in the development of amblyopia.

Overall, these analyses indicate that while there is little evidence of astigmatism-related deficits and thus no evidence of recovery from deficits in subjects CJ and CR, the data from AA indicated notable deficits at baseline, and improvement over time once clear sensory input was restored through use of eyeglasses. This finding is particularly notable because subject AA was 11-years-old when he received in glasses to correct his astigmatism, several years older than age 7, which previous research has indicated as being the upper age limit for plasticity associated with recovery from astigmatism-related deficits. However, it should also be noted that even after 1 year of treatment, AA still demonstrated evidence of perceptual deficits: e.g., letter acuity was 20/63 at baseline, and 20/32 at 1 month and 1 year. These data suggest that although plasticity can occur in a child of this age, there may be limits on the amount of change that can occur with the introduction of clear sensory input, as full recovery was not observed.

3.5 Factors Associated with Plasticity: Evidence from Other Paradigms

The data presented here suggest that, for 5- to 14-year-old age children with astigmatism-related visual deficits, restoration of clear sensory input through prescription of eyeglasses did not result in significant improvements in vision for the astigmatism group as a whole, although there was some evidence of improvement in at least one child who had relatively severe deficits at the start of the study (i.e., subject AA).

Research on plasticity associated with visual deprivation in humans has primarily been reported in the clinical vision literatures in ophthalmology and optometry, with little crossover into the experimental psychology literature. I believe that research and theory from the experimental psychology literature can provide important insights and new ways of thinking about plasticity associated with visual deprivation and recovery, and that this contribution could be particularly meaningful in the case of recovery from visual deprivation, and in the search for effective treatments for deprivation-related visual/perceptual deficits. In this section, I discuss some theoretical perspectives on plasticity and perceptual change from the experimental psychology literature, and explore ways in which these perspectives could be applied to research and theory on the visual deprivation and recovery. Specifically, I will focus on theory regarding factors necessary to induce plasticity.

Bedford (1993a, 1993b, 1995) addressed the question of what conditions are necessary for plasticity to occur. In her general "Perceptual Learning Theory", she argues that all changes in perception that result from experience must result from the detection of an internal perceptual error that needs to be corrected. She applied the theory to plasticity associated with perceptual adaptation and suggested that plasticity results when two conditions are met. The first condition, following the work of others (Wallach, 1968, Welch, 1978), is that a sensory discrepancy must be detected. However, she reasoned that the presence of a sensory discrepancy alone does not provide sufficient evidence to the perceptual system that plasticity is necessary, i.e., it does not allow us to distinguish between an internal perceptual error that needs to be corrected vs. the detection of something new about our environment. Thus, she reasoned further that a second condition that must be met is the detection of a violation of constraint internalized by perceptual systems, which often involves knowledge about objects. It is the violation of internal constraints that provides the cue that there is an internal perceptual error that needs to be corrected.

I believe that applying Bedford's theory to deprivation-related plasticity can provide important insights regarding factors that might lead to greater plasticity in recovery from deprivation. To apply the Perceptual Learning Theory framework to recovery from deprivation, we should start by asking two questions regarding the conditions that lead to plasticity: (1) what is the sensory discrepancy that is detected, and (2) what is the internal constraint that is violated by the discrepancy. With regard to recovery from deprivation, I believe that the sensory discrepancy introduced is the improved optics and resolution provided at the level of retinal inputs through use of eyeglass correction for astigmatism, thus resulting in new sensory patterns of stimulation. However, as Bedford (1993) reasoned, detection of this new sensory information may simply indicate that there is something new about the environment; how do our perceptual systems know that the discrepancy is reflecting an internal perceptual error that requires correction or plasticity? What is the internal constraint that is violated by this discrepancy? I believe that the internal constraint that is violated relates to object constancy. In general, our knowledge of the world and objects in the world tells us that they do not change suddenly, i.e., the same objects should not result in different patterns sensory stimulation over time. If they do, this would signal the violation of an internal constraint, and signal the perceptual system that there is an internal error that requires correction, as predicted by Perceptual Learning Theory.

How is the Perceptual Learning Theory framework helpful in pointing towards ways in which we might induce more plasticity in recovery from deprivation? If plasticity results when a discrepancy is detected, and when that discrepancy violates an internal constraint, perhaps we could use methods to enhance detection of these conditions. I believe that one method of accomplishing this is through use of discrimination learning paradigms.

In the present study, the initial hypothesis was that with restoration of normal visual experience (eyeglass wear to correct for optical effects of astigmatism), improvement in visual perceptual functioning would occur. The basis for this assumption was that normal visual experience in early childhood is sufficient to support normal development of perceptual capabilities, and that perhaps restoration of normal input would also be sufficient for the development of these perceptual capabilities in previously visually deprived children. However, if subjects were beyond the sensitive period for this type of change, perhaps more intensive visual stimulation e.g., through use of discrimination learning trials, would be required in order for perceptual systems to detect the sensory change, or error. As noted in the introduction, the literature on discrimination learning has provided ample evidence that visual perceptual abilities in adults can be improved through intensive training paradigms.

Reinke (1999) recently applied Perceptual Learning Theory (Bedford, 1993a, 1993b, 1995) to plasticity associated with discrimination learning. She suggested that the perceptual error detected in these studies was that there was "not enough sensitivity". The information regarding violation of internal constraints in these paradigms may come from top-down processes, such as attention, feedback, and task-related demands and information. Bedford (personal communication, 2002) has suggested that perhaps the internal constraint is that two different objects should not look exactly the same. For example, if task related information indicates that the two objects are different, but sensory inputs provide information that they look the same, this condition would signal that there is an internal error (not enough sensitivity, as suggested by Reinke, 1999) that needs to be corrected. Perhaps this type of top-down information regarding detection of sensory discrepancy and violations of internal constraints would provide the additional motivation for perceptual change in subjects who are towards the end or beyond the sensitive period for recovery from astigmatism-related deprivation.

The literature on perceptual adaptation may also provide further clues for development of effective treatments for deprivation-related perceptual deficits. For example, Banks (1988) noted that adult studies of perceptual adaptation report that complete adaptation occurs in some instances but not others, i.e., perceptual aftereffects are less than 100% of the distortion experienced. Banks suggests that complete adaptation can occur under the following conditions: (1) when experimentally induced distortions mimic the effects of normal developmental processes, and (2) when there is adequate visual and visuomotor experience to determine what sort of distortion has occurred and how to compensate for it. Perhaps these principles might also be relevant for recovery from deprivation. The data presented here indicate that full recovery of perceptual abilities did not occur in children with astigmatism-related perceptual deficits treated with eyeglass wear. Applying Banks' hypothesis to the interpretation of these data suggests that perhaps the failure to observe improvement in these subjects is due in part to the fact that either the restoration of clear input through use of eyeglasses does not adequately mimic normal development or that subjects did not receive adequate visual experience in order for them to determine what type of sensory change had occurred.

How might we create a situation for these subjects that would more accurately mimic normal development of perceptual abilities, and heighten detection of changes in their visual experiences, i.e., increase the likelihood that they will detect a perceptual error? In experimental paradigms, this is often achieved through feedback, whether it is through trial and error motor interactions with their environment in prism adaptation experiments, or through experimenter-provided error feedback in discrimination learning paradigms. In the case of recovery from deprivation, the use of direct feedback regarding detection of visual stimuli seems most appropriate, and therefore discrimination learning paradigms might be a useful means of providing subjects with feedback regarding the accuracy of their perceptions, and cues to the presence of perceptual errors.

In summary, research and theory on plasticity from the experimental psychology literature suggests several factors that may increase plasticity in subjects recovering from the effects of visual deprivation. These ideas focus on the conditions necessary for plasticity to occur, such as detection of an sensory discrepancy (Banks, 1988, Bedford, 1993a, 1993b, 1995) and violation of internal constraints that would signal that there was an internal error that required correction, or plasticity (Bedford, 1993a, 1993b, 1995). The most efficient way to increase the likelihood that these conditions would be detected by perceptual systems might be through use of discrimination learning paradigm. With use of this type of paradigm, feedback and task demands could be used to stimulate top-down processes to increase the chance of detection of internal perceptual errors, and gradual increases in discrimination difficulty over time could be used to simulate normal developmental changes and to ensure continuous detection of perceptual error over time. In addition, visual perceptual experience could be directed at targeting specific perceptual deficits.

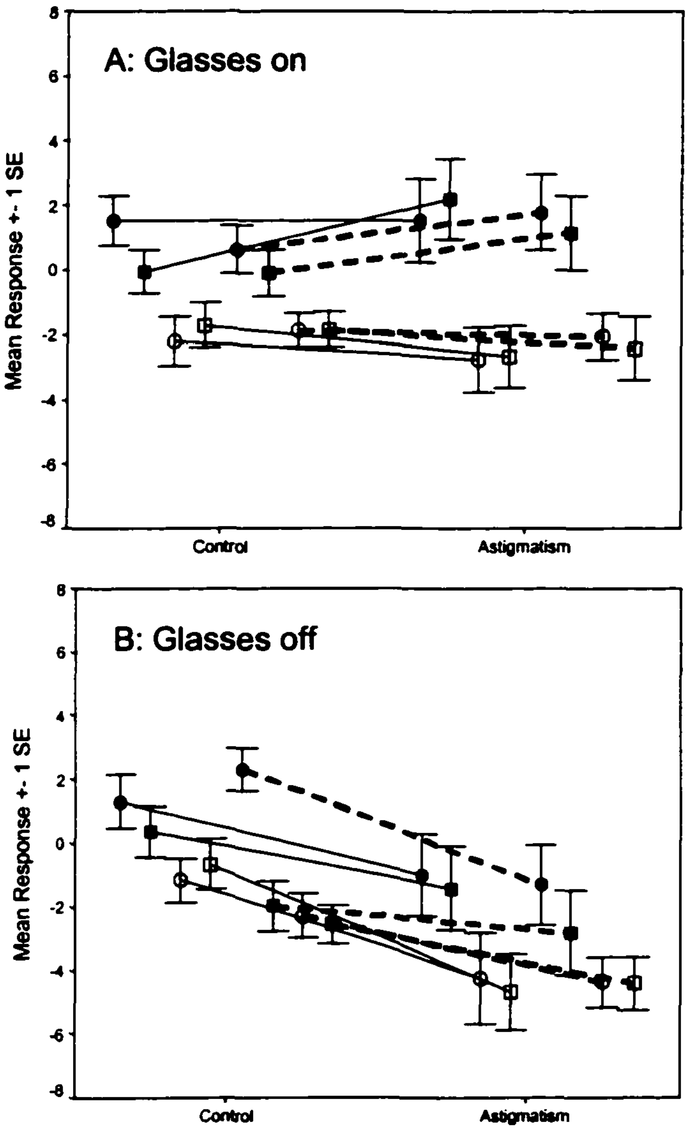
Recently, researchers have begun to evaluate the effects of this type of treatment strategy on patients with deprivation-related perceptual deficits (e.g., Polat et al., 2001). The data presented in the present study, specifically baseline data, have essentially provided a blueprint of the nature of perceptual deficits that occurs as a result if astigmatism-related deprivation, and provide important information for development of discrimination learning type treatment for these deficits.

3.6 Plasticity Associated with Adaptation to Spatial Distortion

This research also addressed the extent to which children adapt to the shape distortion induced by cylinder lenses, i.e., lenses that correct for the optical defocus caused by astigmatism. I predicted that there would be no difference in mean response for the control group with glasses on vs. glasses off (since there is little or no cylinder in the lenses), and that the astigmatism group would not differ from the control group in the glasses-off condition at baseline because minimal distortion is produced by an astigmatic cornea or lens. However, I predicted that, if the task were sensitive enough to measure the distortion induced by the cylinder lenses, the astigmatism group, on average, would tend to choose more vertically elongated stimuli as "the perfect circle", since cylinder lenses that correct for with-the-rule astigmatism vertically compress images.

Results for the control group were as predicted: mean responses were close to 0 (i.e., true circle), and did not differ between the glasses-on and glasses-off conditions, nor did they differ from baseline to 1 month. The astigmatism group tended to choose more vertically elongated stimuli in the glasses-on condition at baseline, as predicted, indicating that the task was sensitive enough to measure the distorting effects of the cylinder lenses. However, the data suggest that children in the astigmatism group perceive the circles differently than the control group when they are not wearing their glasses: on average, the astigmatic children perceived vertically compressed stimuli as more circle-like, whereas the children in the control group chose stimuli close to the true circle as circle-like. This result is puzzling, because the original prediction was that children in both groups would choose a stimulus close to the true circle when glasses were not worn, i.e., when no distortion was induced. As previously discussed, astigmatism of the eye does not cause distortion like cylinder lenses because the amount of distortion perceived is dependent in part on the distance between the unequal curvature and the location where light enters the eye, i.e. the pupil, and the greater the distance from the pupil, the greater the distortion. Thus, when unequal curvature is located on the cornea, distortion is minimal (Guyton, 1977), whereas when the unequal curvature is located further from the pupil, e.g., with eyeglass lenses, distortion is greater. However, even if astigmatism at the cornea did distort form perception in a manner similar to the distortion induced by cylinder lenses, one would assume that the children would have adapted to this distortion.

Several additional post hoc analyses were conducted to verify this unusual finding. For example, in Figure 34, I plot mean scores for the control group and the astigmatism group on each type of trial (baseline/follow-up x stimulus type (outline circle/checkered circle) x start stimulus (-12/+12)). As you can see from the comparison of the two plots, in the glasses on condition, mean measurement by trial type is similar for the astigmatism vs. the control group: lines connecting measurements for each trial type for control and astigmatism groups are generally flat. In contrast, in the glasses off condition, regardless of trial type, the astigmatism group tended to choose more vertically compressed stimuli as the "perfect circle". These patterns are consistent across trial type, despite what appear to be strong main effects of start stimulus (filled vs. open symbols), such that subjects tend to choose more elongated stimuli when they start the task from the +12 stimulus (filled symbols), and they tend to choose more compressed stimuli when



■ = Checkered Circle Stimuli, Subjects started task with +12 Stimulus
□ = Checkered Circle Stimuli, Subjects started task with -12 Stimulus
● = Outline Circle Stimuli, Subjects started task with +12 Stimulus
○ = Outline Circle Stimuli, Subjects started task with –12 Stimulus
---------- = Baseline Measurements
______ = 1 Month Measurements

Figure 34. Mean form perception by trial/stimulus type and group. Mean +/- 1 standard error of form perception responses for each trial/stimulus type under glasses-on (A) and glasses-off (B) conditions.

they start the task from the –12 stimulus (open symbols). Thus, this pattern seems quite robust, occurring regardless of stimulus type, start stimulus, or time of measurement.

One possibility is that the effects of orientation-dependent blur might influence shape perception in the astigmatic subjects. For example, in the case of the myopic/mixed astigmats, increased blur for horizontal lines may make true circles appear taller (top and bottom of the circle would appeared blurred than the sides), thus causing them to choose flatter stimuli to compensate for the effects of the blur. Also, since these subjects have poorer acuity for horizontal even with glasses on, the effect might have been observed for both the glasses-on and glasses-off conditions. Hyperopic astigmats, who appear to focus between horizontal and vertical (based on presence of equivalent deficits for both orientations) may not have such a bias related to blur. However, it is possible that this type of effect is driving the data for the astigmatism group towards selection of flatter stimuli, and thus explaining the observed effects.

Regardless of this unexpected finding, baseline data indicate that the children in the astigmatism group perceive shape differently when the glasses are on, in comparison to when they are off, and that this distortion is in the direction as predicted by the type of distortion the lenses induce. In addition, the data are also clear with regard to measures of perceptual adaptation to these lenses – there was no indication in the data that the children were adapting to the distortion over a 1 month period. However, Perceptual Learning Theory (Bedford, 1993a, 1993b, 1995) would suggest that, since perception in the astigmatism group with glasses-on appears to be accurate, no perceptual error would be detected, and therefore, the plasticity would not be expected to occur.

Finally, from a clinical perspective, these data suggest that the form distortion induced by the cylinder lenses provides minimal disruption to perception of form. From a theoretical perspective, the absence of conditions that would lead to plasticity did not allow us to determine the extent of plasticity related to perceptual adaptation in children in the present study. I hope that future studies directly comparing perceptual adaptation for adults vs. children will help determine if there is a sensitive period for this form of visual plasticity, as there is for other forms of visual plasticity, such as plasticity related to visual deprivation and to recovery from the effects of deprivation.

3.7 Conclusions

Since the publication of key research studies by Mitchell, Freeman and their colleagues in the early 1970s (Freeman et al, 1972, Mitchell et al, 1973), only a handful of studies have addressed questions regarding the effects of astigmatism-related deprivation on visual/perceptual development and function in humans (e.g., Gwiazda et al., 1986, Dobson et al., 2002). Presumably, this is due to the limited subject pool for such studies due to the low prevalence of astigmatism in the general population. The presence of such a high prevalence of astigmatism among some Native American Tribes has allowed us to conduct studies that have led to a better understanding the influence of astigmatism on visual perceptual development, and have allowed for prospective studies on plasticity for recovery from the effects of astigmatism-related deprivation. Ultimately, the goal of this line of research is to gain better insight into the development and organization of the human visual system and the conditions that lead to visual plasticity, and from a clinical perspective, to develop effective treatments for astigmatism-related visual deficits, and other forms of deprivation-related visual/perceptual deficits.

The results of the present study suggest that recovery from the effects of astigmatism-related deprivation in 5- to 14-year-old children are minimal at best with simple re-introduction of clear vision (i.e., eyeglass treatment). However, I hope that the discussion presented here has highlighted areas of research and theoretical ideas that may lead to treatment alternatives for children and adults who are beyond the sensitive period for recovery from these types of visual perceptual deficits. Many of these ideas are discussed primarily in the experimental psychology literature, which has focused little on deprivation-related plasticity. Greater interaction of research and theory on visual plasticity between clinical vision and experimental psychology could lead to significant advances for both research traditions.

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