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**ASSESSMENT OF INFANT VERNIER ACUITY USING THE TEST-PEDESTAL
APPROACH**

by
Elizabeth Bauer

**A dissertation submitted to the Graduate Faculty in Psychology
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy, The City University of New York.**

2000

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Abstract**ASSESSMENT OF INFANT VERNIER ACUITY USING THE TEST-PEDESTAL
APPROACH**

by

Elizabeth Bauer**Advisors: Professors Louise Hainline & Israel Abramov**

The present research sought to a) investigate a new technique for the assessment of vernier acuity in infants and b) use this tool to determine whether the limitations underlying vernier acuity are the same as those limiting detection. In this method, the “test-pedestal approach”, contrast detection thresholds are measured for a “test” stimulus and for a “pedestal” stimulus; we used a line and an edge as the test and pedestal, respectively. These detection thresholds are then used to predict the low contrast vernier acuity of an edge vernier stimulus, created by adding the test to the pedestal. Vernier acuity of this stimulus is also measured, at several contrast levels, in order to determine the veracity of this method. This technique also provides a way of ascertaining whether the limitations which underlie detection are the same as those which underlie position (i.e. vernier) acuity.

In the first experiment, contrast detection thresholds of the test and the pedestal for five adult subjects were measured using this approach, modified for use with infants. In addition, we measured vernier acuity thresholds at several different contrast levels. The results showed that, with some exceptions, our modified procedure reproduced the results achieved in previous studies. We

then extended the research in our second experiment by measuring the test and pedestal detection thresholds of fifteen 4-6-month-old infants. In the third experiment we measured the vernier thresholds of nineteen 4-6-month-old infants at four different contrasts levels. We were then able to use our detection data to determine whether we could predict low contrast vernier acuity from our detection thresholds. The results of these experiments indicated that, as with normal adults, low contrast vernier acuity was in close agreement with the detection threshold of the test. However, the detection results from our edge pedestal were surprisingly high. This necessitated a fourth experiment, in which we investigated whether the inflated pedestal thresholds were an artifact of infant preference. This experiment, in which two other detection stimuli were tested, indicated that the high edge thresholds were probably a function of the unattractiveness of the edge stimulus.

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My thanks to James Gordon for his encouragement and accessibility and to Lynne Kiorpes for her scientific and editing expertise.

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world beyond the classroom.

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*This dissertation is dedicated to my mother, Paula Miller, who always loved me.
I wish you were here to share this with me, Mom.*

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[1]

INTRODUCTION

1.1 What is hyperacuity?

There are many physiological factors which might place limits on our best visual performance. For example, it seems obvious that the spacing between the photoreceptors of our retina might place a serious constraint on our visual acuity. This, however, is not the case. In 1975, Gerald Westheimer coined the expression "hyperacuity" to refer to performance on visual tasks which was far better than what our photoreceptor spacing would imply. These tasks usually involve the ability to discriminate the spatial offset of a line or point in relation to another reference line or point. There are a variety of these tasks such as vernier acuity, bisection acuity and spatial alignment, and these tasks use stimuli which range from points, gratings and single line stimuli, to Gabor patches. Thresholds for the normal adult fovea may be as low as 3-5 arc sec for these tasks. Initially this "subpixel" resolution (Ciuffreda, Levi and Selenow, 1991) was conceived of as a paradox: how could the eye deal with stimuli which produced offsets that were smaller than the spacing between photoreceptors? However, Morgan (1991) explains that this is not necessarily a problem, because the visual system spreads the light distribution of the stimulus over several receptors, whose pooled responses extract the centroid of the distribution. In fact, he explains that the input must be blurred over several receptors in order for hyperacuity to be achieved; if the visual system had better resolution (and less blur) such fine thresholds would not be possible. That is, if the optics were such

that the stimulus fell on a single receptor, fine positional accuracy would be impossible.

What are the benefits of having such fine resolution? Morgan (1991) hypothesizes that being able to detect a small discontinuity along the horizon is evolutionarily adaptive, allowing us to discern things such as threats or food sources. As evidence he points out that animals living in habitats with far horizons, like plains-dwelling creatures such as ostriches and antelopes, have large eyes with greater image magnification. This would aid them in detection of small discontinuities such as an oncoming predator. He does admit that this is not a very strong argument, since a larger eye would also have increased resolution. Morgan also cites McKee (1987) who believes that our need for quick and accurate detection of small stimuli (based on the typical tasks or things that humans do) has necessitated hyperacuity development. If this is the case, then the psychophysical analog to detecting discontinuities along the horizon might be vernier acuity, which is typically the detection of an offset with lines, or "bump detection", in which a bump is detected along a straight line. Following this line of reasoning, however, does not help explain our remarkable acuity on tasks such as bisection, or discriminations made with spatially separated stimuli. Morgan (1991) proposes that in a visual scene with many elements, some of which may partially occlude others, it is important to be able to determine which parts of a given object go with any other parts. This proposal is similar to that suggested by McKee (1987). The psychophysical analog to this kind of situation might be the task of determining colinearity between two lines which are spatially

separated by a gap, another task in which we show extremely low thresholds.

1.1.1 What Kind of Tasks Measure Hyperacuity?

There are many different types of tasks which allow us to achieve thresholds thought of as hyperacuties (Morgan, 1991). Some of the differences are in the stimuli which are used. They may be static or dynamic, dots, lines, or edges, or there may be configurational differences such as abutting lines versus spatial gaps. Some of the differences are in the task itself. In some cases the subject is asked to detect an offset or a direction of orientation, or they are asked to bisect a space, or align the stimuli. Although thresholds for these tasks may be similar, it is possible that the underlying mechanisms in these tasks are different. In fact, it is now believed that there is not one "hyperacuity mechanism", but rather a constellation of skills, which may have similar thresholds (Watt, 1984). The following is a brief summary of some of the distinctions between different types of hyperacuity as suggested by Morgan (1991).

Vernier Acuity

A traditional vernier acuity task is usually one in which the subject must detect non-collinearity between two abutting lines or edges (Figure 1a) and determine its orientation. However, it has also been used to describe an orientation judgement on spatially separated features such as dots. Morgan (1991) believes that this is inappropriate, and has recommended restricting the term "vernier acuity" to the task of non-collinearity detection (in abutting lines) to keep it separate from orientational acuity. Although lines are very often used,

Figures 1a-e. Examples of different hyperacuity stimuli. a) Line vernier acuity, b) extrapolation acuity, c) "bump" acuity, d) periodic vernier acuity, e) chevron acuity.

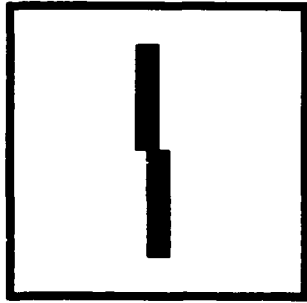


Figure 1a

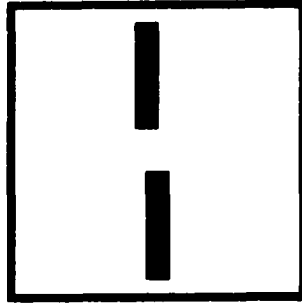


Figure 1b

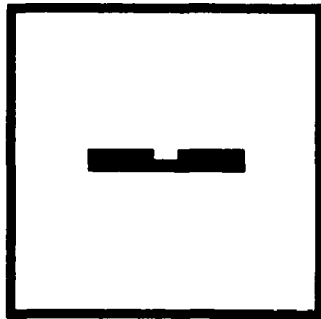


Figure 1c

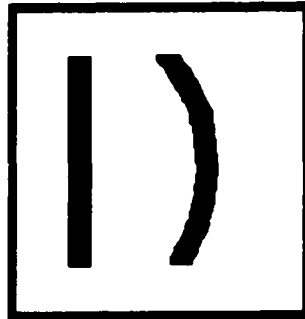


Figure 1d

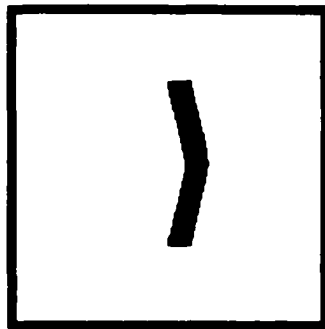


Figure 1e

this task can also be done with edges.

Extrapolation Acuity

This is the term Morgan uses to describe the task in which there is a separation between the two lines in a vernier target (Figure 1b). It is referred to as extrapolation acuity because, in essence, the subject must determine whether there is an offset between two stimuli if the ends were extrapolated towards each other. Beyond a specific range, gap size has a strong effect on thresholds; as the distance between the two stimuli increases, thresholds rise (Morgan, 1991).

"Bump" Acuity

As the name indicates, this is the detection of a "bump" or protrusion, somewhere along a straight edge or line (Figure 1c). This might really be comparable to the real-life task of detecting a discontinuity along the horizon. Sometimes these stimuli are created by overlaying a sinusoid on an edge, creating an indentation at the frequency of the sinusoid. Thresholds from this task are similar to those obtained with a traditional vernier task (Morgan, 1991).

Periodic Vernier Acuity and Curvature

In periodic vernier acuity, a subject must discriminate between two stimuli: a straight line and a line which has some sinusoidal modulation. Figure 1d shows an example of a periodic vernier stimulus where the curved line has a sinusoidal modulation of one cycle. This is somewhat different from a traditional vernier task because orientation judgement is an important component in a traditional vernier task, whereas in a periodic vernier task there is no orientation judgement involved. In a curvature task, the subject must determine which of

two lines is more curved. These two tasks seem closely related to each other (Wilson, 1985). Curvature modulation is a special case of the periodic task and indeed, thresholds for both tasks are similar and both decrease quickly when the stimuli are presented peripherally (Tyler, 1973; Wilson, 1985).

Orientational Acuity

Although an orientation judgement is involved, this is a different task from traditional vernier acuity. In this task, the subject must judge whether the stimulus (a pair of dots, a line or an edge) is tilted away from some base orientation, usually vertical. This base orientation is represented as an internal standard which must be compared with the external stimulus to make a decision. We obtain better thresholds when comparisons are made to either a vertical or horizontal standard than to an oblique standard (Orban, Vandebussche & Vogels, 1984).

Spatial Interval, Spatial Frequency, Length and Width Acuties

In this task, the subject must determine whether a delineated spatial interval is smaller or larger than a standard, which could be either implicit or explicit. A particular case of interval acuity would be bisection acuity, in which the subject must determine whether a stimulus (usually a dot or line) is to the left or right of the center of a delineated interval. Similarly, in length or width acuity tasks, the subject must determine whether a line stimulus is longer or shorter (or narrower or wider) than a standard. Analogous discriminations can be made in the spatial frequency realm, using gratings as stimuli.

Chevron Acuity

The stimulus in this task is a vertical line which is bent in the middle, shifting half of the line either to the left or right of the other side of the line (Figure 1e). The subject's task is to judge whether the direction of the line segment on one side of the bend is to the left or right of the line segment located on the other side of the bend (Watt, 1984a). Subjects also achieve thresholds which are close to those obtained with traditional vernier acuity (Watt, 1984a).

Stereoacuity

Stereoacuity gives us depth information which is relative to some fixed point, not absolute depth information. Typically, the stimuli for this kind of task consist of two lines presented dichoptically, with the disparity for one line larger than the disparity of the other (McKee, Welch, Taylor, and Bowne, 1990). We achieve very fine levels of stereopsis, with thresholds similar to those obtained in vernier acuity tasks (McKee et al., 1990). However, it is interesting to note that although thresholds may be similar, some researchers believe that stereopsis is regulated by a mechanism or mechanisms which are different from those which regulate other hyperacuties (Gwiazda, Bauer, & Held, 1989).

1.2 What Does the Study of Hyperacuity Tell Us?

1.2.1 Hyperacuity as a Measure of Spatial Vision.

Although there are many aspects of spatial vision which are worthy of investigation, the topic of position acuity has remained an extremely important one. As mentioned above, there are many different tasks which are used to study hyperacuity. Morgan (1991) points out that rather than a single

mechanism, hyperacuity is best viewed as a series of mechanisms, which may be illuminated by the different types of tasks which result in hyperacuity. Performance in these types of tasks produces thresholds which are lower than those obtained in grating acuity tasks, hence the name hyperacuity; the thresholds obtained are usually 5 to 10 times finer than either the spacing between photoreceptors or the cutoff spatial frequency (Westheimer, 1975). Researchers have used hyperacuity tasks to try to illuminate the mechanisms of spatial vision because, originally, the question of how a system is able to perform "sub-pixel" resolution (Ciuffreda et al., 1991) has been of major interest. Also, hyperacuity tasks are thought to reflect cortical processing (Levi, Klein & Aitsebaomo, 1985) whereas tasks like grating acuity could reflect limitations as early in the system as the retina. This means that performance on hyperacuity tasks could provide a window onto cortical mechanisms. Lastly, Marr (1982) proposed that the mechanisms which allow us to discriminate with such accuracy on hyperacuity tasks are the same mechanisms subserving our ability to analyze form and shape. Hyperacuity therefore seems to be an appropriate medium to investigate the visual system's capacity for spatial perception as well as precision.

1.2.2 The Use of Hyperacuity to Distinguish Among Visual Deficits.

Another reason to study hyperacuity is that performance has been shown to differentiate among degraded visual systems. The amblyopic visual system, that of the normal adult periphery, and the infant visual system, are all systems which show degraded performance with respect to the normal adult fovea.

Research has indicated that there are similarities between the performance of the infant visual system and that of the amblyope and normal periphery which may shed light on possible underlying mechanisms. First we will look at the research on amblyopia.

Many investigators have studied hyperacuity as a way of uncovering the underlying mechanisms of the visual deficit known as amblyopia. Amblyopia refers to a condition of reduced visual acuity in an eye which appears physically normal (Ciuffreda et al., 1991). It is characterized by abnormalities or losses of spatial vision with accompanying abnormalities in binocular vision. Since the emphasis in amblyopia is on a loss or abnormality of the form (or space) sense, it is logical that amblyopes should show poor performance on hyperacuity tasks (Levi & Carkeet, 1993). Although amblyopes demonstrate deficits in grating acuity, what is interesting is that the hyperacuity loss is greater than the grating acuity loss.

Performance on vernier tasks demonstrates a distinction between two types of amblyopia believed to have different etiologies. The development of amblyopia is associated with different ocular disturbances such as strabismus (eye turn), anisometropia (unequal refractive error between the two eyes), or more severe monocular deprivation such as cataract or aphakia. The onset of a strabismus may result in different images falling on corresponding retinal areas; anisometropia may deprive one eye of receiving high spatial frequencies; cataract or aphakia may result in a deprivation of almost all spatial pattern information of the image (Boothe, Dobson, & Teller, 1985). Any one or

combination of these conditions may result in amblyopia but, interestingly, onset of these disturbances does not always result in amblyopia. Two important factors concerning whether or not amblyopia develops are 1) the severity of the imbalance between the eyes and whether fixation alternates between the two, and 2) the time of onset of the precipitating conditions (Ciuffreda et al., 1991; Levi & Carkeet, 1993). Strabismic amblyopia is believed to be a result of (or correlated with) an eye turn, whereas anisometropic amblyopia appears to be due to the difference in refractive error between the two eyes. Both may result in degraded visual performance, but the deficits characterizing each appear to be different. Different tasks, especially hyperacuity, have shed light not only on the differences in deficit, but also on the different mechanisms underlying the deficit.

One of the differences between strabismic and anisometropic amblyopes has been in a comparison of their responses on grating acuity and Snellen acuity (Levi & Klein, 1982b). Although Snellen acuity is not thought of as a hyperacuity task per se, Levi & Klein (1982a, b, 1983) demonstrate the close tie between Snellen acuity and hyperacuity tasks such as vernier offset and bisection tasks. In a comparison of Snellen and grating acuity, they found that normal eyes and those of anisometropic amblyopes displayed a high correlation between performance on the two acuity tasks. Furthermore, when Snellen and vernier acuity are plotted against each other, the line fit to the data had a slope of 1, indicating that the mechanisms subserving performance on these two measures seemed to be affected to the same extent (Levi & Klein, 1982b). This was true for both normals and anisometropes. It might appear then, that the deficits in

grating and Snellen are due to the same process. The pattern for strabismic amblyopes differed, however. Although there was also a high correlation between their performance on grating and Snellen acuity, the slope of the line fit to the data was not 1, indicating that there was not a one-to-one correspondence between grating and Snellen acuity for strabismic amblyopes. There is a greater loss of Snellen acuity with strabismic amblyopes relative to their grating acuity. In other words, since grating acuity and Snellen acuity appear to be degraded differentially, this implies that these losses are not due to the same underlying cause. As a note of interest, the studies of Levi and Klein (1982b) and Bedell, Flom and Barbeito (1985) also demonstrated that faulty eye movements and eccentric fixation could not account for the pattern of results in strabismic amblyopia.

Levi & Klein (1982a, b, 1983) further extended their results by demonstrating the connection between performance on Snellen acuity and that of other hyperacuity (or position acuity) tasks. The data from the above studies showed that both vernier acuity and bisection acuity were affected in the same way as Snellen acuity. Levi & Klein (1982b, 1985) then plotted performance of vernier acuity as a function of grating acuity. They obtained results similar to those of the studies using Snellen acuity relative to grating acuity. That is, performance on these tasks resulted in a slope of unity for anisometric amblyopes, but thresholds were considerably degraded for vernier or bisection acuity, relative to grating acuity, for strabismic amblyopes. These studies give credence to the idea that Snellen acuity and position acuity, demonstrated in

hyperacuity tasks, are closely tied (Ciuffreda et al., 1991). Also, Levi and Klein (1982b) point out that the differences between anisometric and strabismic amblyopes were not due to very low grating acuities in anisometric amblyopes. Rather, the distribution of grating acuities for the two groups was very nearly the same, but there was a wider range of Snellen acuities for the strabismic amblyopes. From this they concluded that there is an additional loss in positional information for strabismic amblyopes beyond their loss of resolution (Levi & Klein, 1982b). Additionally, it was observed that the loss of vernier acuity is spatial frequency specific; that is, the inability to utilize positional information is much worse at high frequencies (Bradley & Freeman, 1985a). As a side note, studies have also shown that there are deficits in the normal periphery in hyperacuity tasks (e.g. Levi, Klein & Wang, 1994a, b). These losses appear to be similar to those suffered by strabismics, but not anisometropes, and it could be that their neural bases are similar.

1.2.3 What Do We Know About Hyperacuity in Infants?

Another visual system which shows degraded performance, compared to normal adult foveal vision, is that of the infant. It has been suggested (Levi et al., 1985), that performance on hyperacuity tasks reflects cortical processing. If this is so, it is useful to study hyperacuity in infants because it may provide more information on their cortical visual processing. To study hyperacuity in infants, researchers have typically used the task of vernier acuity with abutting lines or gratings. However, researchers have obtained differences in both the absolute values measured for vernier acuity and the developmental trend. Some

researchers (Manny & Klein, 1984; Skoczenski & Aslin, 1990; Zanker, Mohn, Weber, Zeitler-Dreiss, Barth, Nieuwenhuizen & Fahle, 1991) have found vernier acuity for 3-month-old infants to be in the range of 22-25 min of arc; however Shimojo & Held (1987) observed thresholds as low as 8 min of arc for the same age group. Using single-bar stimuli in both static and dynamic conditions, Skoczenski & Aslin (1992) reported thresholds ranging from 22.8 to 51.4 arcmin. Also, some researchers have found differences in the slope of development of vernier acuity (Brown, 1997). This is most likely due to differences in both stimulus configuration and methodology among studies. For example, stimulus motion is very attractive to infants and has been used in several studies to enhance the appearance of vernier offsets (Manny & Klein, 1985; Shimojo, Birch, Gwiazda & Held, 1984; Shimojo & Held, 1987; Zanker et al., 1992). In the Shimojo et al., (1984) and Shimojo and Held (1987) studies, stimuli were set up so that, theoretically, the infant would detect the motion only if the offset were detected. However, although the use of motion helps to engage infant attention, there is one serious drawback: it may confound sensitivity to motion with position detection (Zanker et al., 1992). Skoczenski and Aslin (1992) offer two possibilities for how dynamic stimuli may result in lower thresholds than static stimuli in vernier tasks. First, it is possible that a coarse-grained spatial mechanism might feed into a finer-grained motion detection mechanism. This would detect the moving offsets, even if the motion detection mechanism wasn't as fine-grained as a hyperacuity mechanism. Alternatively, a finer grained spatial mechanism might feed into a coarser-grained motion detector. The

spatial mechanism would detect the offsets and the motion would be also be detected, which might increase its attractiveness to the infant. Either of these might explain why motion produces superior performance in infants.

What is of considerable interest is not just the absolute values of infant vernier acuity, but also the patterns of development for both grating and vernier acuity with respect to each other. With the caveat that motion possibly confounds the results, studies indicate (Shimojo & Held, 1987; Zanker et al., 1992) that vernier acuity starts out worse but then improves more rapidly than grating acuity. Vernier acuity also has a longer developmental time course, not reaching adult levels until about 10 years of age, according to Levi and Carkeet (1993). However, Zanker et al. (1992), found that vernier acuity was almost adult-like by 5 years of age. This is similar to a study of macaque monkeys by Kiorpes (1992) in which it was found that vernier and grating acuity approached adult levels at about the same age, approximately 40-60 weeks. Using the four to one rule (Teller & Boothe, 1979), this translates to about four years of age for humans, although Kiorpes cautions that this may not be strictly appropriate in this case. Using behavioral methods, grating acuity appears adult-like by approximately 3-5 years of age, although physiological methods show maturation somewhat earlier. Skoczenski and Aslin (1990) suggest that the term infant "hyperacuity" may actually be a misnomer, because optimal performance in both grating and vernier tasks are below the Nyquist frequency for infants. In fact, they prefer to view vernier acuity in infants as a measure of pattern discrimination rather than actual hyperacuity.

However, although there may be agreement on the overall development of vernier acuity, the exact point at which the crossover occurs to better vernier acuity has varied among studies. The data of Shimojo and Held (1987) show a crossover at 4 months whereas Zanker et al. (1992) show this at 15 months. Also, although grating acuity is similar in both Zanker et al. (1992) and Shimojo and Held (1987), vernier acuity was consistently lower in the Zanker et al. (1992) study. The variability in these results may be due to use of dynamic stimuli (Skoczenski & Aslin, 1992), repetitive gratings (rather than single bar stimuli) or both (Zanker et al., 1992). Skoczenski and Aslin (1992) also point out that differences in the rate of development for grating and vernier acuity may reflect task demands rather than sensory processes. They suggest that this is because grating acuity is really a detection task whereas measurements of vernier acuity are a discrimination task. However, although the results of Shimojo and Held (1987) and Zanker et al. (1992) do agree in that vernier acuity started out less than grating acuity in young infants, their results differ from those of Manny and Klein (1984) who found that even in infants as young as 2 weeks of age, vernier acuity was higher than grating acuity, for static gratings. Manny and Klein (1984) also reported lower grating acuities than those usually obtained. Additionally, they altered the stimulus conditions between age groups, increasing the difficulty of comparison. Their later study (Manny & Klein, 1985) measured vernier acuity using dynamic stimuli and a three-alternative tracking paradigm, but unfortunately they didn't measure grating acuity in the same infants. Further support for the developmental pattern observed by Shimojo and Held (1987) has

come from animal studies (Kiorpes & Movshon, 1987; 1988) which observe a similar trend. However, although there has been an emphasis in the research on determining the point at which vernier acuity becomes superior to grating acuity, an important point should be noted. Kiorpes (1992) has suggested that comparison of the “crossover” in vernier acuity reported in the previous studies is actually problematic, probably reflecting differences in units of measurement more than task demands.

Given all of these caveats, what can we say about the similarities between amblyopes and infants, and can we utilize hyperacuity to further our knowledge about infant visual processing?

1.3 Two Degraded Visual Systems - The Link Between Amblyopes and Infants

What is the uniting factor underlying the degraded performance in these visual systems? The performance of the infant visual system appears to be more like that of strabismic amblyopes, while anisometropes perform more like adults with blurred vision (Levi & Carkeet, 1993). As with strabismics, there is a dissociation between grating and vernier acuity in the infant. The reduced vernier acuity that infants demonstrate is not simply related to their relatively poor spatial resolution. This being the case, do the theories explaining strabismic amblyopes and their performance on hyperacuity tasks help to illuminate the deficits of infant vision?

Evidence from infant development indicates that major changes occur in the development of the fovea, especially in the size and spacing of receptors (Abramov, Gordon, Hendrickson, Hainline, Dobson, & La Bossiere, 1982;

Hendrickson & Yuodelis, 1984; Yuodelis & Hendrickson, 1986). Some researchers underscore the importance of these changes in accounting for the visual deficits of infants (e.g. Wilson, 1988). However, there are also cortical changes occurring simultaneously. Synaptic development starts out as very diffuse, with many connections made and then honed down to adult levels over several years, presumably due to visual experience (Huttenlocher, de Courten, Garey, & Van der Loos, 1982). Although by no means conclusive, it is also interesting to note that adult levels of vernier acuity are not achieved until after 5 years of age according to Zanker et al. (1992); Levi and Carkeet (1993) report that adult levels are reached at about 10 years of age. This is the approximate age range at which cortical connections seem to reach their mature levels (Huttenlocher et al., 1982). The fovea appears to reach full development by about 4 years of age (Yuodelis & Hendrickson, 1986), reaching maturity sooner than the cortex. Could it therefore be surmised that cortical development places the limiting parameters on position acuity?

Shimojo and Held (1987) suggest that in infants, subcortical undersampling as well as immature cortical connections may lead to their degraded performance in vernier acuity tasks. Kiorpes (1992a) suggests that deficits in infant vernier acuity may be related to developmental changes in cell density as early in the visual system as the ganglion cells. Blakemore & Vital-Durand (1986) demonstrated that both contrast sensitivity and spatial resolution in cortical cells improved with age; Kiorpes (1992a) suggests that these changes reflect improvements in the responses of the photoreceptors. Levi and Carkeet

(1993) propose that since the developing eye undergoes such drastic changes - receptor size and spacing, eyeball lengthening and interpupillary distance changes - plasticity of cortical connections may be required in the infant. The result of this plasticity, however, may be an array of cortical filters which is either undersampled or topographically jittered (or mislabeled), so that position information is not accurately encoded. It may then make sense that position acuity does not reach mature levels until these developmental changes have taken place.

The amblyopic visual system, however, differs anatomically from the infant visual system. Foveal development (Bedell, 1980; Hess & Baker, 1984; Hendrickson, Movshon, Eggers, Gizzi, Boothe, & Kiorpes, 1987) and LGN development (Hendrickson, et al., 1987; von Noorden & Crawford, 1992; von Noorden et al., 1983) appear mature and normal both physiologically and anatomically, although the LGN does display some anatomical deficits. The main deficits of the amblyope appear in the visual cortex, both anatomically and physiologically (Hendrickson et al., 1987; LeVay, Weisel & Hubel, 1980; Movshon et al., 1987). Although infants display deficits much earlier in the visual system than amblyopes, Levi & Carkeet suggest that the connection between the infant and amblyopic visual systems may be that position information is uncertain, which could be a result of undersampling and/or topographical irregularities at the level of the cortex. Kiorpes & McKee (1999) explain that it is sufficient to explain the hyperacuity data of anisometric amblyopes with a loss of high spatial frequency filters. However, strabismic demonstrate an additional

loss not explained by a shift from high to middle spatial frequency filters. Kiorpes & McKee (1999) describe two possible additional deficits: 1) there are too few cortical receptors to adequately sample the image (undersampling) and 2) there are a sufficient number of receptors but they are not arranged in an orderly fashion; either they are topographically jittered, mislabeled, or both (uncalibrated disarray). Levi and Carkeet (1993) postulate that the filter mechanisms for both infants and amblyopes differ from those of normal adults in three ways. First, they propose that filter mechanisms for high spatial frequencies are missing, implying an increase in neural blur because the image is sampled by larger filters. Psychophysical evidence for this has been found for infants (Wilson, 1988) and in both types of amblyopes (Levi & Klein, 1990a,b; Wilson, 1991). The second and third differences, applying to strabismic but not anisometric amblyopes, are that the remaining filters are undersampled and irregularly spaced. It may be that sparse and irregular foveal sampling in the infant (and the normal periphery) is transmitted to the cortex, resulting in positional uncertainty. Zanker et al. (1992) agree that the increase in vernier acuity with development necessitates major changes in the spatial grain of the visual system. They also point out, in agreement with Skoczenski and Aslin (1995), that the variability in infant studies on vernier acuity makes it premature to conclude whether limitations on vernier performance are due to cortical or retinal factors. In the strabismic amblyope, sensory obstacles which interfered with development of normal connections may result in permanent positional uncertainty.

1.4 What Is the Connection Between Contrast and Vernier Acuity?

The emphasis in most current models explaining spatial vision is how localized spatial filters respond to stimuli. A major underlying premise is that limitations on hyperacuity will be based on the contrast response of these filters (Levi et al., 1994). As Morgan (1991) points out, it is rather hard to draw any strong conclusions on the effects of contrast in all hyperacuity tasks because there has been no large, all encompassing study to investigate the many different hyperacuities under the same conditions. Rather, there have been many studies using different configurations and different tasks, so conclusions are difficult to draw. What can be derived is that there are some tasks which are contrast-dependent over almost our whole visual range, including tasks like vernier acuity with abutting lines and bump acuity (Morgan, 1991). Then there are other tasks, e.g. orientation discrimination for gratings or spatial-frequency discrimination, in which contrast no longer effects thresholds past a certain level. The point at which thresholds saturate is approximately 3 times greater than their detection threshold (Morgan 1991). Morgan also proposes a couple of theories to explain these results. In one variant, Morgan theorizes that contrast dependence is seen if a task measures true positional acuity. However, if the mechanisms underlying the task are not limited by position, then these tasks would not be contrast dependent either. An alternative position supposes that a task like bump acuity, or vernier acuity with abutting lines, is more like a luminance detection task; in this case, thresholds would decrease with contrast, because the cue is becoming stronger. Morgan (1991) ultimately hypothesizes

that contrast dependence may be linked to scale invariance; tasks that are not scale invariant (e.g. vernier acuity with abutting lines) show contrast dependence, and vice versa. He posits that there are both contrast-dependent as well as contrast-independent mechanisms, and that in any particular task both mechanisms could be involved, but the task may determine which mechanism carries greater weight. With vernier acuity, which is not scale invariant and can be viewed as a detection task, one would expect to find a strong effect of reduced contrast on vernier performance. This is in fact the case. It has been revealed that contrast plays a large role in the ability to make the fine position judgments necessary for hyperacuity tasks, specifically when abutting stimuli are used (Morgan, 1991). Thresholds in this task improve with increased contrast and worsen under conditions of low contrast. This has been measured many times in adults (e.g. Wilson, 1986), but only one study (Skoczenski & Aslin, 1995) has even superficially looked at the possible contrast dependence of vernier acuity in infants. This was done in order to clarify whether their results on intrinsic blur could have been explained by reduced contrast; they determined that this was not the case. However a systematic study of the contrast dependence of vernier acuity has never been done in infants.

1.5 Hyperacuity and The Test-Pedestal Approach

Over the years, researchers have sought to determine the underlying mechanisms of and limitations on hyperacuity. Although we have remarkable hyperacuity, it is not perfect, so there must be some factors which limit our abilities. As mentioned previously, since hyperacuity is thought to reflect cortical

mechanisms, it is possible that the main factors which limit hyperacuity are cortical in nature (Levi et al., 1985), although front end limitations may also play a role. For example, it is hypothesized that the receptor sampling array of the visual cortex may be undersampled in infants and strabismic amblyopes, two groups who demonstrate degraded position acuity. It is also believed that this array may be topographically irregular in these visual systems, resulting in uncertain position information (Levi & Carkeet, 1993). Previous models (e.g. Geisler, 1984; Klein & Levi, 1985) have provided insights into some of the underlying mechanisms of hyperacuity and some of the deficits seen in the amblyopic visual system (e.g. Wilson, 1991). A key factor in any of these models is the aforementioned contrast dependence on abutting vernier acuity, and that the limits on hyperacuity will be determined by the contrast response of the underlying mechanisms (Levi et al., 1994). If this is the case, could the deficits seen in other visual systems (e.g. amblyopic, peripheral, infant) also be accounted for on the basis of the visibility of the vernier stimulus? Can our sensitivity, as defined by the contrast detection threshold of the vernier stimulus, predict our hyperacuity thresholds?

A technique used by Klein et al. (1990a) provides an intriguing way to connect a contrast detection threshold with the vernier acuity threshold. This is a paradigm which, rather than using extended gratings, uses the same stimulus for both the detection task and the hyperacuity task. That is, the sensitivity of the system is measured with the same localized stimuli as those used in the vernier task. Referred to as the "test-pedestal approach", it is an unusual way of looking

at the task of abutting vernier acuity. It involves thinking about the vernier stimulus, e.g. an edge with an offset, as the combination of an edge plus the addition of a line (see Figure 2). A vernier stimulus which is a line with an offset is considered as the combination of a line plus the addition of a dipole. The hyperacuity task is then conceived of as detection of the test (line) in the presence of a masking pedestal (edge). This is similar to Morgan's (1986b) hypothesis that vernier acuity is akin to a luminance detection task, where thresholds actually decrease with increased contrast because of masking. Indeed, the vernier task could really be understood as a detection task when the contrast of the pedestal equals zero. This technique is based on the earlier work of Klein (1989) in which he strongly recommends the use of "multipoles" as stimuli for testing visual performance.

Klein (1989) defines five visual patterns (ramp, edge, line, dipole and quadrupole) that are related to each other as "multipoles" mathematically. Each higher level multipole (starting with ramp at the low end and ending with quadrupole at the high end) is the first derivative of the previous multipole. For example, a line is the first derivative of an edge and a dipole is the first derivative of a line.

These forms are not extended in space, as sinusoids would be, but rather are localized within a small area. Klein has suggested that these stimuli could be used to measure sensitivity of the visual system in a way that is similar yet complementary to use of the contrast sensitivity function (CSF). The CSF is the outcome of testing with sinusoidal grating stimuli, whereas Klein's stimuli are

Figure 2. The edge vernier stimulus can be conceptualized as the addition of a line (the test) to an edge (the pedestal).

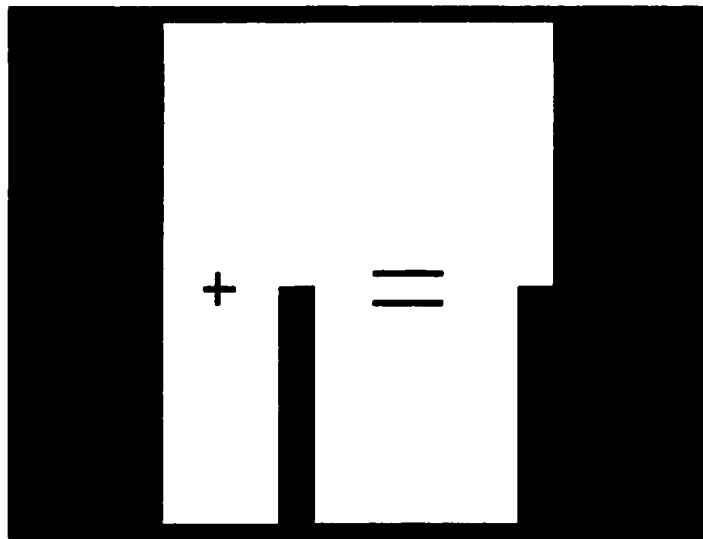


Figure 2

localized. Of course, there are certain assumptions that have to be made in order to connect multipole and sinusoid sensitivity, the most important of which is that multipoles and sinusoids are detected by the same mechanisms. Given this caveat, Klein lists several advantages to the use of multipoles to measure visual performance. For example, he cites that anyone could be tested with a high contrast line multipole, as long as it was scaled appropriately by altering the viewing distance. Therefore you could get a measure for any degraded visual system (e.g. infant, adult periphery) with the same stimuli, which would make the determination of norms easier. The same cannot be said of the CSF, in which certain spatial frequencies could not be tested because they would not be visible to patients with degraded visual systems. Another advantage which Klein (1989) refers to is that of "joint probabilities". He points out that having five different stimulus patterns to test provides more information; for example, once norms have been established, it would be more informative to find out that a patient had a normal threshold with one type of stimulus and an abnormal threshold with another type of stimulus. Additionally, Klein (1989) has found that contrast thresholds for the higher order multipoles are closely connected to the hyperacuity threshold of the vernier stimulus in which they are the "test". He suggests that this might possibly make hyperacuity testing unnecessary. He also notes that these stimuli are easier to create than sinusoids, especially those of high spatial frequency. An additional advantage of multipoles over the CSF is that CSF results may be variable, depending upon how many cycles of a given spatial frequency can be displayed. Because they are so localized, there is no

need to worry about the number of cycles; the entire multipole is always displayed. This would be helpful for standardization of the multipole sensitivity. These are not even all of the advantages to the use of multipoles. Indeed, Klein (1989) argues that the use of multipoles might ultimately replace the contrast sensitivity function (CSF) as a technique to measure visual functioning.

Using the test-pedestal technique, Klein et al. (1990a) demonstrate that varying the contrast of the pedestal allows us to understand how detection of a thin line is associated with hyperacuity. They investigated whether edge vernier acuity could be predicted from the detection of the "test" and the "pedestal"; that is, detection of a line and an edge respectively. They also used the same approach to examine line vernier acuity, using a line as the pedestal and a dipole as the test. When using these stimuli, they did find that performance in the detection task could predict performance on abutting vernier acuity at low contrast for the normal adult fovea. Using this approach they also found that the ratio of the detection thresholds of the test and pedestal has been shown to be an estimate of spatial pooling, or Ricco's area (Klein et al., 1990a).

The test-pedestal approach allows us to predict vernier thresholds without the drawbacks of either the filter or photon model approaches. Essentially we reformulate the vernier task into one of *detection*; that is, detection of the offset in the presence of a masking pedestal. It is easy to see that this becomes a pure detection task when the pedestal contrast equals zero. Pictorially it is simple to conceptualize an edge vernier stimulus as an edge plus the addition of a line. Mathematically there are two things we have to rely on in order to make

this work: 1) the multipole definition of contrast, given by

$$C = (L_{\max} - L_{\min}) / [(L_{\max} + L_{\min}) / 2]$$

which is twice the Michelson contrast and 2) the Taylor series expansion, which shows that

$$C_E(x + \delta) = C_E(x) + \delta C'_E(x)$$

where C_E refers to edge contrast and δ equals the offset. (Note: Only the first two terms of the Taylor series are used because δ is believed to be a very small amount). That is, the contrast of the edge plus the offset (giving us an edge vernier stimulus) equals the contrast of the edge plus the contrast of the first derivative of the edge (which is the rate of change) times the offset (which is the amount of change). The first derivative of the edge is a line. This achieves the ultimate relationship which is

$$\text{Vernier offset } (\delta) = \text{Line strength} / \text{Edge strength}$$

where strength is based on their multipole definition of contrast. That is, the strength of the edge is simply its contrast in units of percent. The strength of the line is the product of its contrast (in %) times its width (in minutes), in units of %minutes. The width of the line is important because of Ricco's law, which states that, within a small area, there is an inverse relationship between intensity (i.e. radiance) and the size of the stimulus (Levine & Shefner, 1991). For example, within Ricco's area, a small but intense spot will be as detectable as a larger, but more diffuse spot. Within Ricco's area the multipole approach is better for determining perceptual strength than the simple contrast approach (Klein et al., 1990a). Because of the unique relationship between contrast and

size within Ricco's area, a 10%min line within Ricco's diameter is equally visible (perceptually strong) whether it is 1.0 min. or 0.1 min wide. Outside of Ricco's area, this could be a 1.0 min wide line at 10% contrast and be very visible, or a 100 min wide line at 0.1% contrast and invisible.

The test and pedestal detection thresholds can be used to calculate Ricco's area, as mentioned previously (Klein et al., 1990a). If the multipoles are examined with respect to strength units (which is more perceptually appropriate), the strength of a thin line is the product of its width and its contrast. A thin line in this case refers to a line thinner than Ricco's area, or the summation extent. The strength of an edge (or its perceptual visibility) is simply its contrast (multiplied by 100 to have units of percent), because it is too wide to summate over the two side of the edge. If a line is very narrow (within Ricco's area), its contrast is determined by dividing its strength by its width (which is found algebraically from the above definition of strength by solving for contrast). This results in a linear function (in log-log coordinates) with a slope of -1.0. When the line width is wider than Ricco's area, the contrast threshold is simply S_{Po} (the contrast), divided by 100. This results in a function parallel to the abscissa. Together, they create the typical threshold vs intensity (tvi) function which plots contrast detection as a function of line width (Figure 3). Ricco's area is the point of intersection between these two parts of the function. Therefore, mathematically we can say that Ricco's area is the strength of the test divided by the strength of the pedestal at detection threshold. Symbolically we say

$$\text{Ricco's area (z)} = S_{Td}/S_{Po}$$

Figure 3. Theoretical curve for adult contrast detection threshold as a function of line width. Threshold decreases with increased line width, until it reaches an asymptotic level.

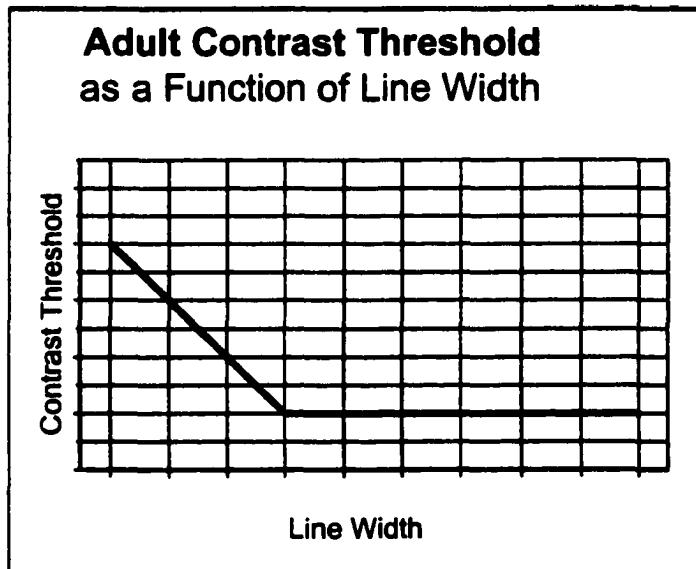


Figure 3

where the "o" signifies that these are strengths measured at their threshold in the detection task, rather than in the vernier experiment. This theory is applicable for any pair of multipoles in which one is the derivative of the other.

1.5.1 Is the Test-Pedestal Approach Effective with Other Visual Systems?

This approach has merit for other visual systems as well. Levi et al. (1994a) used the test-pedestal model in another study investigating hyperacuity in amblyopes and the normal periphery. They found that, with anisometric amblyopes, diminished hyperacuity performance was attributable to increased spatial pooling, (larger Ricco's area), for the test as well as a reduction in local contrast for the pedestal. However, with strabismics and the normal periphery this was not a sufficient explanation. An added source of noise, beyond the sensitivity of the system, such as that due to jitter, undersampling or positional uncertainty had to be postulated in order to fit their data. They found that a combination of undersampling as well as positional uncertainty, on top of the contrast losses, were needed to mimic the losses of strabismics and the normal periphery. This "uncalibrated disarray", coupled with undersampling, is believed to occur at a level past that which handles the contrast mechanism (Levi et al., 1994a). However another study, by Kiorpes, Tang & Movshon (1997) used this approach with normal and strabismic monkeys and found results contrary to those of Levi et al. (1994a). They found that measuring Ricco's area in this manner did in fact predict performance on a vernier acuity task even with strabismic monkeys, in direct contradiction to Levi et al.'s (1994a) conclusions. Their results indicate that the sensitivity of the system, measured in this manner,

was sufficient to explain performance in strabismic monkeys; no other factor needed to be postulated.

1.5.2 The Test-Pedestal Approach and Its Use With Infants.

This research seeks to address several questions. First, we would like to know whether infant performance on a vernier acuity task can be predicted, as it is with the normal adult fovea, by measuring detection thresholds using the test-pedestal approach. This model would allow us to determine whether infant vernier performance can be predicted from their sensitivity at low contrast levels, as in the normal adult fovea, or whether an extra error has to be hypothesized to fit the data. Given the similarities Levi & Carkeet (1993) found between the strabismic and infant visual systems, it might be hypothesized that their performance in this task would be similar as well. However, would infant results be similar to the strabismics of Levi et al. (1994a), or would they be similar to those of Kiorpes et al. (1997) who found that vernier performance could in fact be predicted by detection performance? Second, would we find that the factors limiting detection are the same in the infant as they are in the normal adult? As mentioned in a previous section, vernier acuity has been measured in infants, but only one study looked at the underlying mechanisms contributing to performance (Skoczenski & Aslin, 1995). Their study looked at limitations in the infant visual system using an equivalent intrinsic blur paradigm. They found that blur was not sufficient, by itself, to explain the difference in performance between 3- and 5-month-old infants and adults. However, it did explain the difference between 3-month-old infants and 5-month-old infants. From their

research it was deduced that an additional limitation is necessary to explain infant performance. The test-pedestal approach would allow us to investigate sensitivity as a limiting factor for infant hyperacuity. It would provide us with an assumption-free model, because the same stimuli used to measure detection are used in the vernier task, avoiding any problems of filter size and shape.

Circumventing assumptions about underlying filters is important in infant work where filter parameters are less well defined than with adults. Third, it would allow us to investigate whether contrast affects vernier acuity in infants in the same manner as in adults. We have seen that there is contrast dependence in vernier tasks with adults; does this relationship hold true with infants? It is surmised that it would be, but no systematic investigation has been done on this topic. Finally, use of the multipole approach illustrates the relationships among detection, hyperacuity and Ricco's area. We can use the ratio of the detection thresholds of the test and pedestal to produce an estimate of the spatial integration region (Ricco's area) for infants, under photopic conditions.

1.6 The Research Paradigm

The research presented here investigated whether the test-pedestal approach is an effective technique to use with infants. Since it had previously only been used with adults, it was necessary to alter the method slightly in order to make it more amenable to use with infants. It was believed that a prerequisite to testing with infants was that we should test visually normal adults first, in order to establish an adult baseline with the alterations. Consequently, in the first experiment we tested visually normal adults with the same methods and stimuli,

scaled for adults, as we used with infants. Using this approach, we measured adult test and pedestal detection thresholds and vernier thresholds at eight different contrast levels. Although Klein et al. (1990a) has investigated different combinations of multipoles, we decided to use a line as the test and an edge as the pedestal for our vernier stimulus. This experiment replicated the efficacy of the method, but under the same conditions as those used to test the infants, demonstrating that both the technique and the methodology worked appropriately. In the second and third experiments, we measured the test and pedestal detection thresholds of 4-6 month-old infants and then the vernier acuity thresholds of the same age group at four different contrast levels. Although our test detection thresholds seemed reasonable, the detection thresholds that we obtained for the pedestal stimulus were not what we expected; indeed, they were higher than the thin line test detection thresholds. We hypothesized that these results were because the edge was a less attractive stimulus to infants that we thought it would be. Accordingly, in the fourth experiment, we measured two more detection thresholds, one for a line that was narrower and one for a line that was wider than our original test stimulus. These results helped create a coherent logic to the results that were obtained.

[2]

EXPERIMENT #1 - ADULT OBSERVERS

EXPERIMENTAL DESIGN AND METHOD

In this first experiment, we sought to replicate the results of Klein et al. (1990a) by testing visually normal adults but with the method somewhat altered to be used with infants. This provided us with a baseline for whether the test-pedestal approach was replicable and whether it was still effective with changes made to adjust for infant testing. Using normal adults we measured the detection thresholds of the test (line) and the pedestal (edge), as well as the vernier acuity thresholds of stimuli at eight different contrasts: 8%, 14%, 24%, 40%, 60%, 100%, 148%, and 200% (twice the Michelson contrast). The changes in method are discussed below.

2.1 Subjects

The subjects were six normal adults who worked at the Applied Vision Institute at Brooklyn College; four were male and two were female. One adult had a very anomalous contrast sensitivity function and was possible amblyopic, so his data were excluded from the analysis. Another subject, YB, was color blind (protoanomalous type) but when tested, his results were within one standard deviation of the population mean and he was therefore classified as normal. All of the other subjects were determined to be visually normal through a battery of other vision studies conducted at the Applied Vision Institute. Subjects either had approximately 20/20 visual acuity or were corrected to this during testing. Subjects ranged in age from 16 to 24 years old; Table 1 lists the

Table 1

**Ages of Adult Subjects in
Experiment 1.**

Subject	Age (years)
WS	24
EM	16
GW	17
YB	21
PM	19

age of each subject. All of the subjects were familiar with vernier acuity tasks from their work at the Applied Vision Institute, however they were unfamiliar with and unpracticed in these particular tasks.

2.2 Stimuli

2.2.1 Pedestal Stimulus (Edge).

Although Klein et al. (1990a) used different multipoles in order to create different vernier tasks, we decided to use an edge as the pedestal and a line for the test of our vernier task. We used an edge as the pedestal instead of a line for two reasons. First of all an edge is preferable to a line because it is easier to achieve high levels of suprathreshold visibility. This is not true with a very thin line and so our results are more generalizable with an edge (Levi et al., 1994a). Secondly, it was thought that the large area of contrast would be more attractive to infants and would therefore maintain infant interest more effectively than a line vernier task. The viewing distance for our adult subjects was 190 cm, which produced an edge pedestal that subtended 2.57 degrees of visual angle. The height of the edge extended the whole height of the screen, which was 20.1 cm, subtending a vertical visual angle of approximately 6.06 degrees at 190 cm.

Contrast of the edge was determined by

$$C_{\text{edge}} = (L_{\text{max}} - L_{\text{min}}) / [(L_{\text{max}} + L_{\text{min}}) / 2] \quad (1)$$

where $[(L_{\text{max}} + L_{\text{min}}) / 2] = 50\%$ of the maximum luminance of 75 cd/m^2 . By examining Figure 4 it can be seen that the side of the screen containing the pedestal was divided in half; one half contained the edge, while the adjoining half contained a lighter rectangle. This was done in order to insure that the two sides

of the screen remained the same in space averaged luminance, even if the contrast of the pedestal was altered. This was done to avoid the confound that subjects might discriminate between the sides based on luminance rather than contrast. Although adult subjects can be instructed as to which parameter to base their judgements on, the same cannot be said of infants. As with all of the stimuli used, we were actually interested in the *strength* of the stimulus, not just its contrast. For edges, the strength was simply contrast measured in units of percent.

2.2.2 Test stimulus (Line).

For the test stimulus (line), we used two lines in this task (Figure 5), rather than the single line used by Klein et al. (1990a). This was done to match our vernier stimulus, which consisted of an edge with two offsets rather than just one. It was believed that this would create a vernier stimulus which was more attractive to infants, because there would be more contours to examine. Therefore it was felt that it would be more appropriate if the test stimulus also contained two lines. The length and width of these lines were determined by two factors. First, the length of the lines had to be long enough so that vernier performance was asymptotic (Levi et al., 1994a). Our lines vertically subtended a length of 1.51 degrees at 190 cm, sufficiently long enough to avoid affecting performance on the vernier acuity task. Second, for this technique to be appropriate it is important that the width of the lines falls within Ricco's area, in order to determine whether increased spatial pooling is one of the factors of higher vernier thresholds. Detection of the test (lines) would give us the

Figure 4. Pedestal Stimulus. This edge stimulus is a variation of that used by Klein et al. (1990a) to be more amenable to use with infants. The dotted line on the figure does not appear on the screen; it is shown to indicate how the screen was divided. Stimuli are drawn for illustrative purposes; they are not drawn to scale.

Figure 5. Test Stimulus. These are two examples of the test stimulus, which contains two lines, rather than the one used by Klein et al. (1990a), to be more attractive to infants. The positioning of the lines, both left-right and top-bottom, was random. As mentioned above, the dotted line is not seen by the infant.

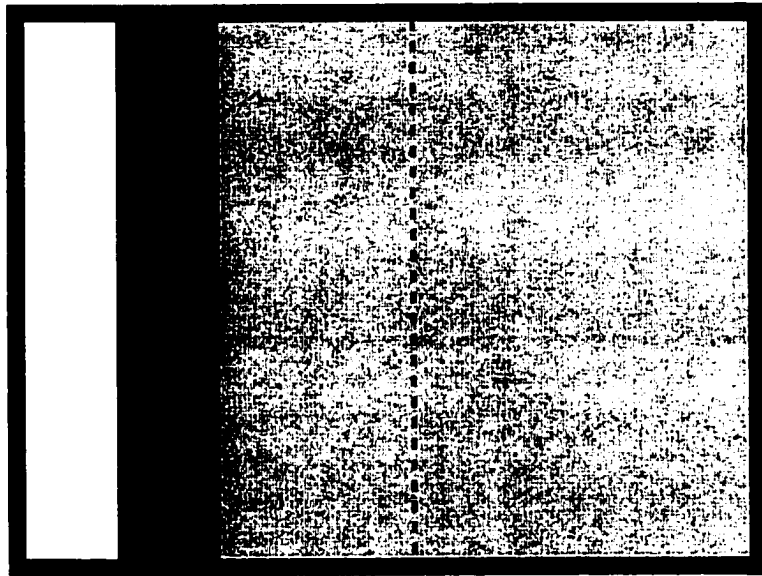


Figure 4

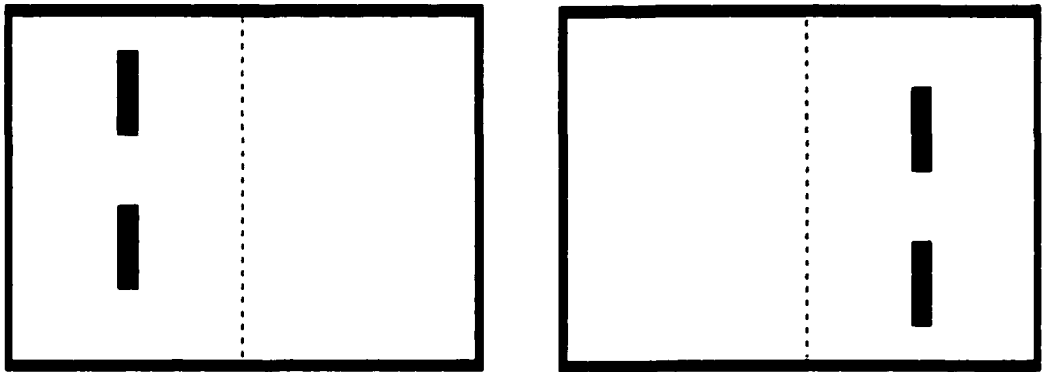


Figure 5

downward sloping line part of the Ricco's area function (see Figure 3) . Since every point in that region is proportional (that is, width x contrast = constant), this detection threshold would give us that whole part of the function. The flat part of the function (parallel to the x-axis) would be determined by the detection threshold of the pedestal as a function of contrast. This is because the edge was created so that its width was larger than Ricco's area. These two points would determine the function and therefore Ricco's area. At a viewing distance of 190 cm, these lines had a width which subtended 0.6 min. This width falls easily within Ricco's area for adults. The two lines were positioned one above the other, separated vertically by 1.51 degrees at 190 cm viewing distance.

Contrast of the line was similar to the above, except that the background luminance when the lines were presented alone was simply the background.

That is,

$$C_{line} = (L_{line} - L_{bgd})/L_{bgd} \quad (2)$$

where L_{bgd} was the background luminance, which was 50% of the maximum, 75 cd/m². Again, *strength* of the line was measured. Line strength was determined as the product of the contrast (in percent) and the width of the line (in min arc), and therefore was in units of %min.

2.2.3 Vernier Stimulus.

The edge vernier stimulus was created in a similar fashion to the edge stimulus, except that it contained offsets (Figure 6). Specifically, the contrast of the vernier stimulus was calculated in the same way as for the edge (equation 1). Adults were tested under 8 different contrast conditions: 8%, 14%, 24%, 40%,

60%, 148% and 200% contrast (this is twice the Michelson contrast). The vernier edge subtended a width of 2.57 degrees when there was no offset. The height of the vernier edge subtended the same visual angle as that of the pedestal, 6.06 degrees.

2.3 Apparatus

The stimuli and procedures were created using VisionWorks, a product of Vision Research Graphics, Inc © 1996. It is a computer package system that is comprised of hardware and software designed specifically for vision research. It includes two monitors: 1) one which displays the stimuli to the subject (Impression 5VX, model # JD156N, 21 inches across) and 2) one which is used to control the stimuli and procedures (FlexScan FX-E7, model # MA-2191, 14 inches across). The stimulus display monitor had a frame-rate of 120 Hz. The software, which is a series of stimulus and procedure modules that can be programmed to work together in different configurations, is run by an IBM-compatible Pentium processor. The stimuli and procedures were programmed by Dr. Shuai Chen.

Luminance was measured and linearization of the display monitor was calibrated using the VisionWorks system. The system hardware includes a photodetector head, power supply and amplifiers, an analog/digital converter board and appropriate cables. This allowed us to measure and adjust the luminance of the monitor until it was 75 cd/m². Linearization was achieved via the program lookup tables.

Figure 6. Vernier stimulus. This stimulus is a variation of that used by Klein et al. (1990a); it contains two offsets in order to increase its attractiveness to infants. The figure is not drawn strictly to scale.

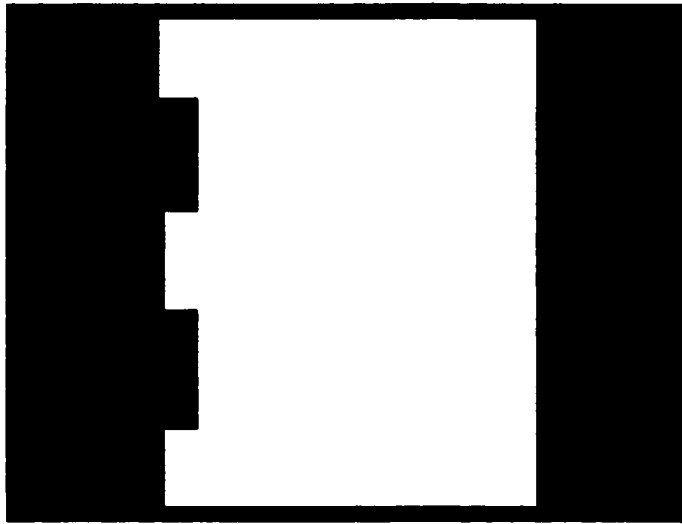


Figure 6

2.4 Procedures

We used a 2-alternative forced-choice paradigm to determine both the contrast detection thresholds of the test and the pedestal as well as the vernier thresholds. Although this technique is often used with adults, it was chosen specifically because it could be used with infants. Adult subjects were seated at a distance of 190 cm away from the screen and wore corrective lenses if needed. Subjects were told that a stimulus (either the lines in the test condition, the edge in the pedestal condition, or the edge with offsets in the vernier task) would appear on either the left or right side of the screen. For the detection task (for either the test or the pedestal), on each trial the subject was presented with a display; on one side of the display the target (either the pedestal or the test) was presented and the other side of the display was a uniform field. The left-right position of the target (either the pedestal or the test) was randomly chosen for every block of five trials. Additionally, in the test detection task, the two lines were randomly positioned either in the top two-thirds, or lower two-thirds of the screen, as they would show up as offsets in the vernier task. Indeed, in the test detection task, the stimuli appeared as if they were the vernier stimulus, but with a pedestal contrast set to zero. The subject's task was to decide on which side the detection stimulus was located. In the vernier task, on one side of the screen the vernier target, an edge with an offset, was presented; on the other side of the display an edge with no offset was displayed. In this task the subject was instructed to decide on which side of the screen the edge with the offsets was located.

The subject held the keyboard on his/her lap and pressed a key in order to start an experimental run. For each trial, a beep would sound in order to establish the beginning of the trial. The stimuli were displayed until the subject made and entered a decision as to the location of the stimulus. Feedback in the form of a single beep was given to the subject when they chose the correct location and a double beep sounded when the location was incorrect. We used a staircase procedure, with approximately 20-40 trials to determine threshold. This allowed us, on average, to run fewer trials for each threshold than the method of constant stimuli, which is what Klein et al. (1990a) used. When the subject began the detection task, the lines started at a contrast of 80% and the edge started at a contrast of 20%. Contrast then increased or decreased accordingly in steps of 0.10 log units. For the vernier task, as in the detection task, the job of the subject was to determine where the target was located; in the vernier task the target was the edge that contained offsets. For each run, the vernier stimulus started with an offset of 5.0 min and then increased or decreased in 0.10 log units. We measured the 71% threshold, based on the 2-up 1-down rule of Wetherill & Levitt (1965). That is, if the subject determined the correct placement of the target for two consecutive trials then the stimulus would decrease in contrast; if the subject was incorrect the stimulus increased in contrast. Although we could have used many reversals to determine adult thresholds, we used eight reversals because this is the method that we wanted to use with infants. It is possible that as few as four reversals would have been enough to obtain a threshold, but review of the infant literature indicated that

thresholds obtained with four reversals may have too much variability and approximately eight reversals has been commonly used. All adults were measured on the test, the pedestal and all eight contrast levels of vernier task, providing us with ten thresholds per subject. The order of which threshold was measured first was randomly generated for each subject. All stimuli and experimental procedures were generated using VisionWorks.

The following modifications of the above procedure were used with infants: We used a 2-alternative forced-choice preferential looking paradigm, in which an observer watched the infant through a camera and made a decision about stimulus placement based on the infant's looking behavior. Use of this technique for contrast detection is based on the premise that an infant prefers to look at something rather than nothing (Teller, 1979) and will therefore attend to a stimulus on one side of the display when the option on the other side of the display is a blank screen¹. There are drawbacks to this method; it is believed that it may underestimate thresholds because it is based on behavior rather than strictly on sensitivity, as visual evoked potentials (VEPs) are, but it has been one of the best methods available for use with an infant population. The infant was held comfortably, facing the computer screen, on the lap of the parent or an assistant, with the infant's eyes approximately 37 cm away from the screen. Parents were instructed not to attract the infant's attention to any particular side of the screen. A camera was placed above the stimulus display and an

1

With infant vernier testing, Skoczenski & Aslin (1992) demonstrated that infants prefer viewing a stimulus with an offset to that without an offset.

observer, blind to the placement of the stimuli, studied the infant's face on a monitor. The observer then made a decision about whether the stimulus was on the right or left side, based on the infant's looking pattern. After the observer recorded the left or right response, feedback was provided as to whether the stimulus had been where the infant was looking. If the infant looking behavior matched stimulus placement, a single beep would sound; if the infant was not looking in the direction of the stimulus a double beep would sound. If it was necessary for the infant's attention to be brought back to the screen, the trial could be started again, or the observer could display various attraction stimuli (e.g., vanes, checkerboards, moving dots) for a time until the baby's attention was recaptured. These attraction stimuli were black and white and usually contained a motion component. They also provided help in determining the infant's looking pattern, especially as the stimulus neared threshold. Occasionally it was necessary for the holder to tap on the middle of the screen to get the infant's attention. When testing began, both the line and the edge started at a contrast of 1.0 (or 100%, twice the Michelson contrast). An infant contributed data to one or more conditions, depending on their state at the time of testing.

For infant vernier testing, each trial started with the vernier stimulus containing an offset of 60 minutes and then increased or decreased in 0.10 log unit steps. We chose a larger offset as our starting point than we did with our adult subjects because we expected that our infant subjects would have higher thresholds. Viewing distance was 37 cm for infants based on previous work on

infant vernier acuity (Skoczenski & Aslin, 1992).

[3]

RESULTS

3.1 Detection Results

The detection thresholds for each subject are plotted in Figures 7 and 8. By examining the figures one can see that detection thresholds for the edge were consistently lower than those for the line, as would be expected. It has been previously shown that thresholds decrease as the line width increases, until it reaches a plateau. In Figures 9 and 10 these detection thresholds were transformed from traditional units into strength units in the following manner. For the edge pedestal, each subject's threshold was simply multiplied by 100 in order to convert it into units of percent. For the test stimulus, strength of a line was calculated by

$$S_T = C_T \times \Delta \times 100\%$$

where C_T is the contrast threshold of the line and Δ is the width of the line. This gives a measure of the strength of the line in units of %minutes. Once these transformations were accomplished, estimations of the spatial summation extent could be calculated. Also, there was some variability in both thresholds across subjects, but no more than that seen in the results of other studies using this method (e.g. Levi et al., 1994a).

Given these thresholds, we can calculate Ricco's area for each of these subjects for the line-edge multipole combination. As mentioned earlier, the spatial summation area can be calculated by

$$\text{Ricco's Area } (z) = S_{T_0}/S_{P_0}$$

Figure 7. Edge (pedestal) detection thresholds for each adult subject. They are plotted in units of contrast on a log axis.

Figure 8. Line (test) detection thresholds for each adult subject. They are plotted in units of contrast on a log axis.

Figure 9. Edge (pedestal) detection thresholds for each adult subject (strength units). They are plotted in units of % contrast on a log axis.

Figure 10. Line (test) detection thresholds for each adult subject (strength units). They are plotted in strength units, which for a line stimulus is the product of line width and contrast.

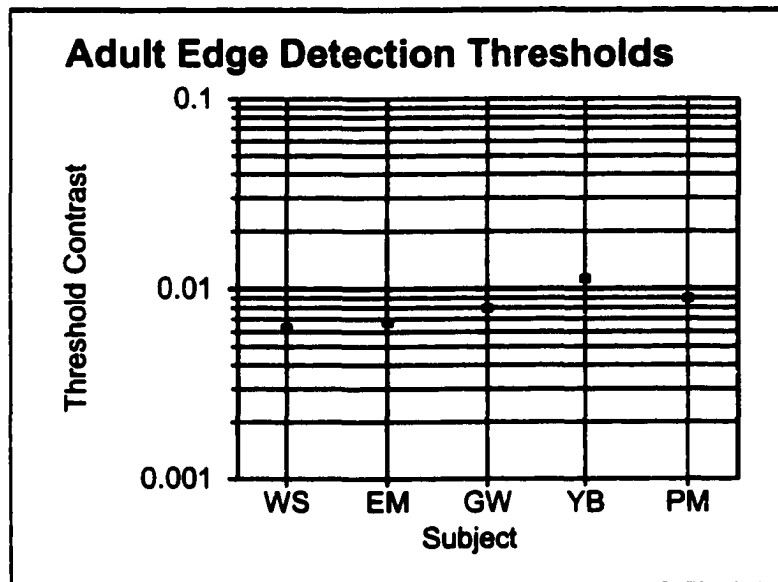


Figure 7

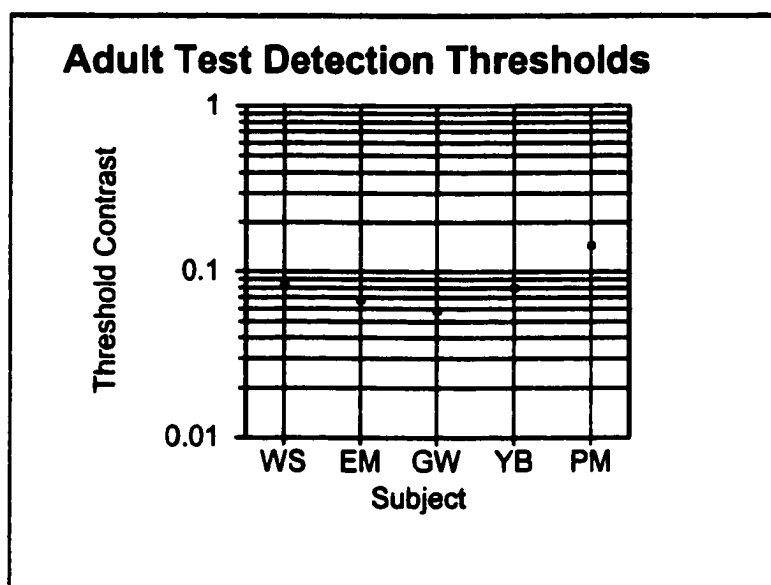


Figure 8

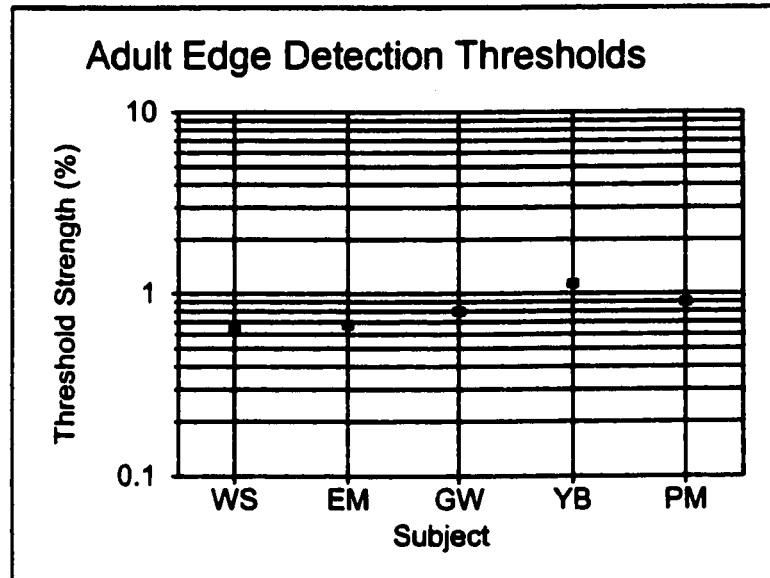


Figure 9

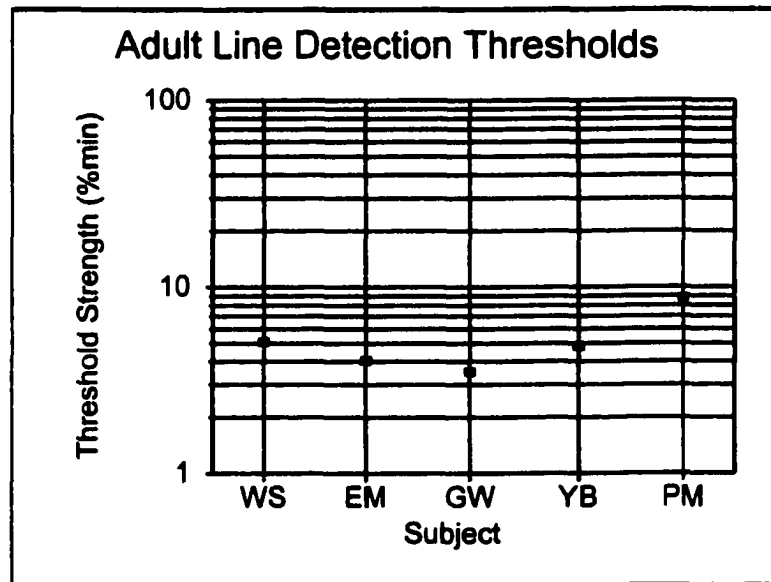


Figure 10

where S_{T_0} refers to the strength of the test stimulus when it is at threshold; that is when the sensitivity to the line is measured in the detection task. Since this is the strength of a line, it is measured in units of %minutes. This is then divided by S_{P_0} which is the strength of the pedestal at threshold as measured in the detection task. This is simply measured in units of percent. The quotient of these two strengths provides an estimate of Ricco's summation extent, in units of minutes. Notice that although these calculations need to be done using thresholds which have been transformed into strength units, the result is a measure of Ricco's area in units of minutes of arc, which is traditionally how it is measured. Table 2 lists the detection thresholds (in strength units) as well as Ricco's area for each of our subjects.

Our thresholds are comparable to those in earlier experiments. To be specific, our edge thresholds ranged from 0.63 - 1.12 %; this is comparable to results from Carney & Klein (1997) which showed edge detection thresholds ranging from 0.87 - 1.71 %. Our line detection thresholds, however, were somewhat higher; they ranged from 3.50 - 8.71 %min whereas those of Carney & Klein (1997) ranged from 0.87 - 1.71 %min. Our line thresholds were also somewhat higher than those of Levi et al. (1994a). This resulted in our obtaining somewhat larger Ricco's areas than Levi et al. (1994a) had calculated.

Thresholds for both detection tasks were somewhat larger than those measured by Klein et al. (1990a), again resulting in our having larger Ricco's areas. This is most likely due to our use of subjects who, although they were not naive to this kind of psychophysical testing, were unpracticed in these tasks. Each of our

Table 2

Adult Test and Pedestal Detection Thresholds

Adult detection thresholds were measured for the edge and line stimuli, in strength units. Ricco's area is calculated for each subject.

Subject	Line Detection Threshold (%min)	Edge Detection Threshold (%)	Ricco's Area (z) $z = S_{Tc}/S_{Po}$ (min)
WS	5.08	0.63	8.06
EM	4.04	0.67	6.03
GW	3.50	0.80	4.38
YB	4.80	1.12	4.29
PM	8.71	0.89	9.79

subjects came in for one session of testing with 20–40 trials per condition, whereas Klein & Levi's subjects were usually highly practiced observers who performed hundreds of trials. Although thresholds were higher, it is probable that this would not change predictability of vernier performance because each subjects' detection threshold would be used to predict their own vernier acuity threshold. Each function would just be shifted a little higher than for the earlier studies.

3.2 Vernier Discrimination Results

As with the detection results, our vernier thresholds were slightly higher than those obtained in previous studies. At the highest contrast (200%), our lowest vernier acuity was 0.19 min (11.4 sec). Although this is not as low a threshold as a highly practiced observer can achieve, it is still a hyperacuity. However, as a check, we were able to compare these results with those from another vernier acuity experiment which was conducted at the Applied Vision Institute of Brooklyn College. In this task, the stimulus consisted of two abutting lines and the viewing distance was 180 cm. Table 3, lists the results of our vernier task when the stimuli were at 200% contrast and the results of this other experiment, for each subject (I. Abramov, personal communication, August 1999).

As examining the table shows, thresholds measured at the Infant Study Center were lower; perhaps this was due to the use of multiple offsets in the vernier stimulus. However, Infant Study Center vernier results were also more variable. Those thresholds measured at the Applied Vision Institute were usually

Table 3

Adult Vernier Acuity Results from Two Different Experiments

Vernier acuity results for adult subjects were measured in two different experiments, using different stimuli.

Subject	Applied Vision Institute Vernier Acuity (min)	Infant Study Center Vernier Acuity (min)
WS	0.452	0.354
EM	0.413	0.193
GW	0.518	0.334
YB	0.467	0.205
PM	0.519	0.199

obtained after many more trials, decreasing variability. This comparison indicates that our thresholds are reasonable estimates of the subjects vernier acuity.

The following figures are the results of the vernier acuity task for each of the eight contrast conditions. They are presented in two different ways: both sets of graphs plot threshold as a function of contrast, but the first set of graphs displays the results measured in traditional units of minutes of arc, whereas the second set of measurements displays the thresholds transformed into strength units, therefore in %minutes. Let us examine the first set of graphs (Figures 11, 12a-e), which contains one graph with all the individuals plotted on the same graph, followed by the individual results. Examination of those graphs indicates that the results of our adult subjects followed the pattern typical of this type of vernier task; thresholds decreased as contrast increased. The points plotted at the far left of each graph are a measure of Ricco's area, calculated in the manner described earlier. The abscissa is the pedestal detection threshold, in percent. The second set of graphs (Figures 13, 14a-e), again with one group graph followed by the individual charts, are a transformation of the traditional vernier units into strength units. Notice how the slope and direction of the functions change with the transformation. This is what Klein et al. (1990a) found, that thresholds actually degrade as contrast increases, when viewed through this transformation. Also notice the unconnected points on the far left of the charts. These plots are the detection thresholds of the test, with the pedestal detection thresholds (in units percent) as the abscissa. These are the points that are

evaluated to see whether the test detection thresholds can predict low contrast vernier thresholds. By examining the individual graphs of threshold in strength units, it can be seen that three out of the five adult subjects had vernier thresholds that were in good agreement with their test detection threshold, at least within a factor of two. This was not true for the data from two of the subjects, EM and GW. The possible reasons for this will be discussed in the next section.

Figure 11. Vernier thresholds for all adult subjects, plotted in minutes of arc. The point plotted at the far left uses Ricco's area, calculated using the formula $z = S_{T0}/S_{P0}$, as the ordinate and the pedestal threshold as the abscissa.

Figures 12a-e. Vernier acuity thresholds for individual subjects, plotted in minutes of arc. a) Subject WS; b) Subject EM; c) Subject GW; d) Subject YB; e) Subject PM. Again, Ricco's area is plotted as the far left data point.

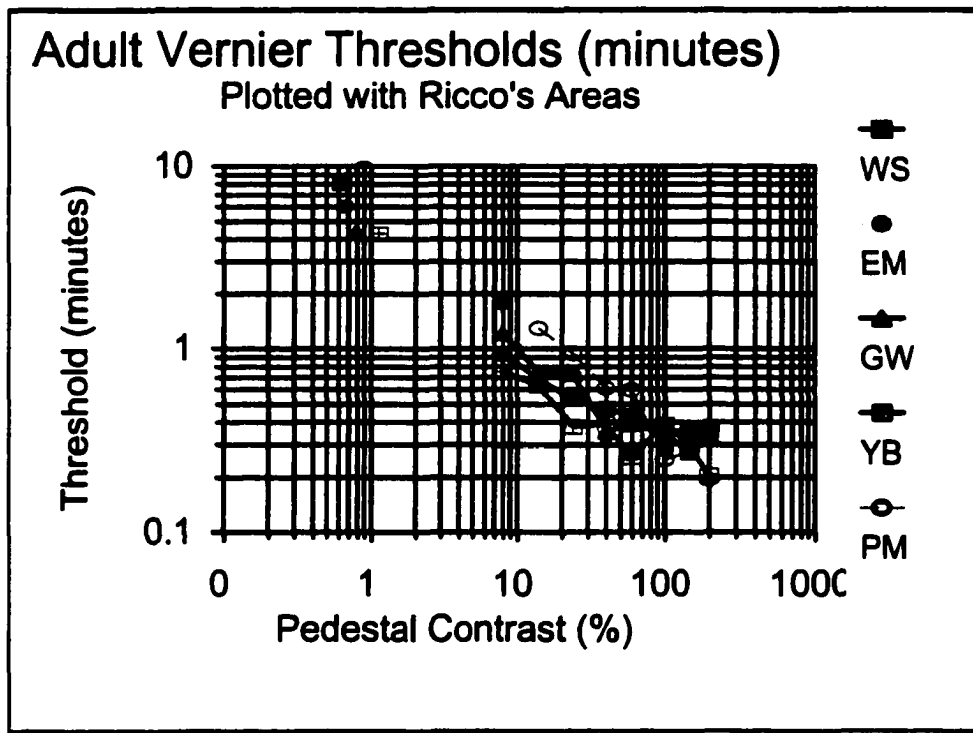


Figure 11

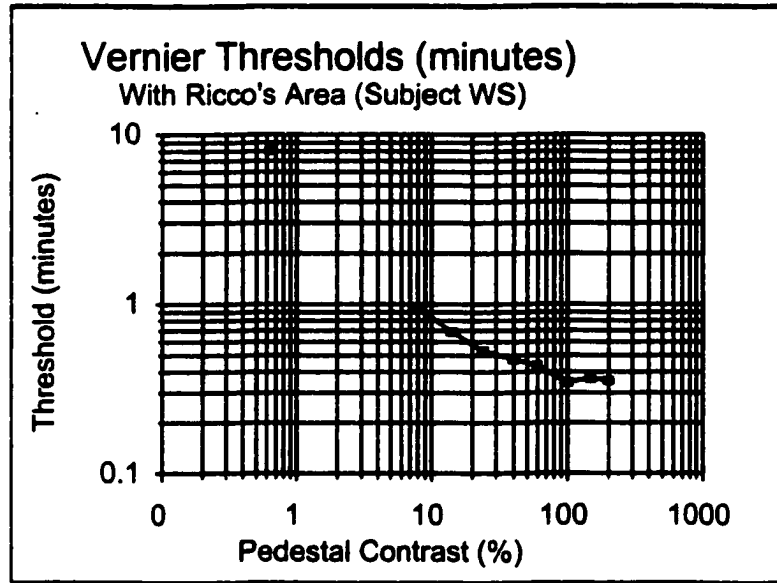


Figure 12a

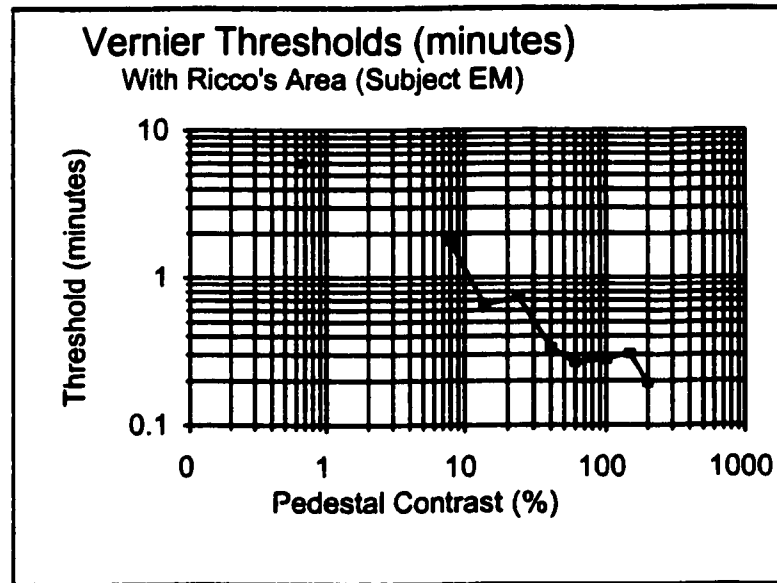


Figure 12b

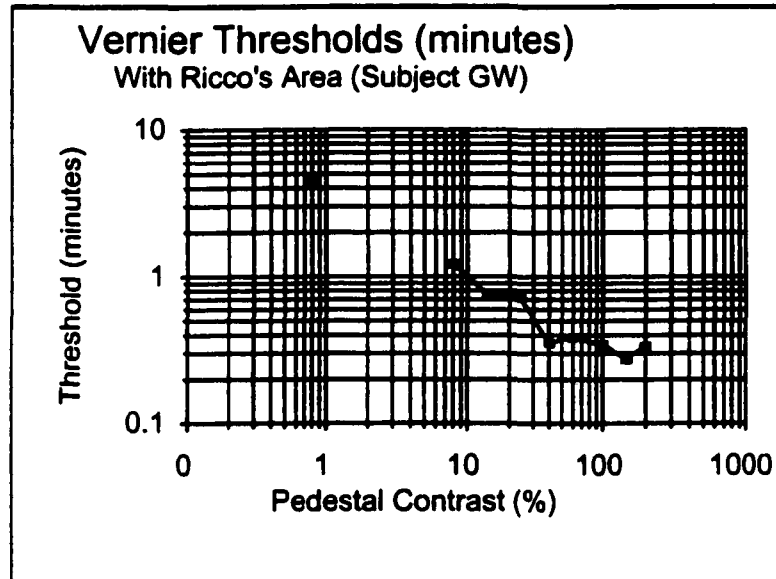


Figure 12c

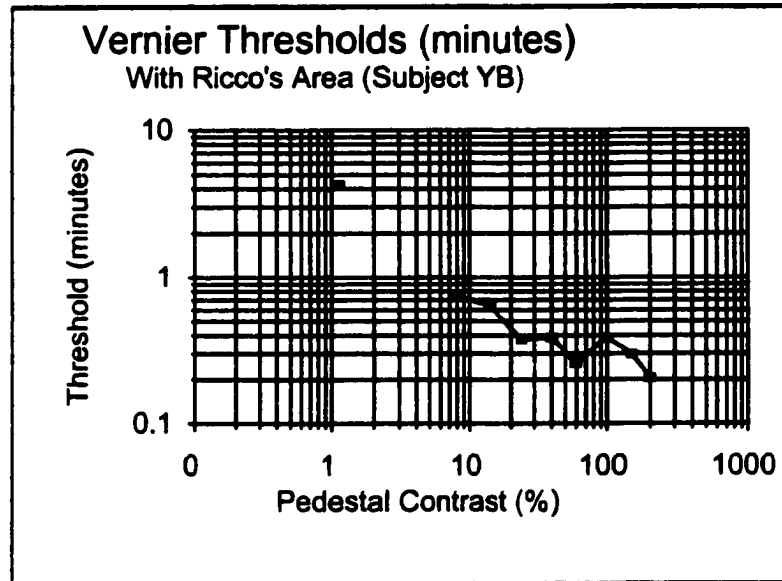


Figure 12d

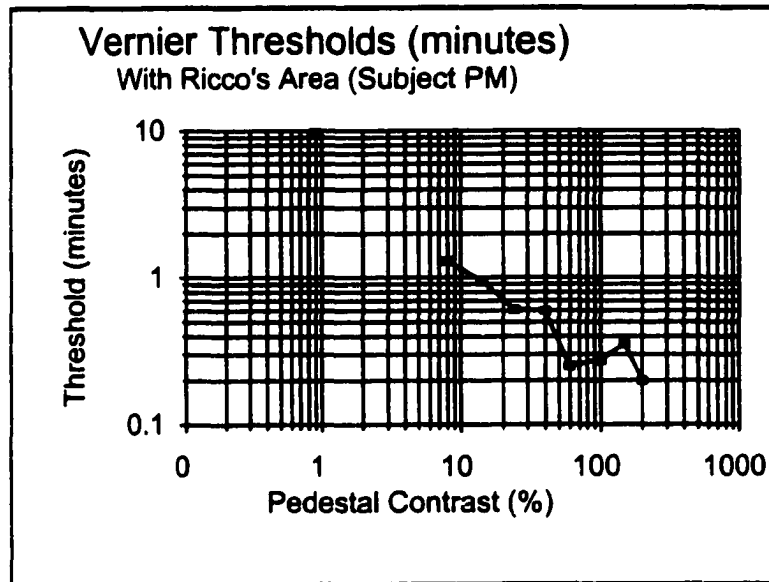


Figure 12e

Figure 13. Vernier thresholds for all adult subjects, plotted in strength units of %min. The point plotted at the far left is the test detection threshold; the abscissa is the pedestal detection threshold.

Figures 14a-e. Vernier acuity threshold for individual subjects, plotted in strength units of %min. a) Subject WS; b) Subject EM; c) Subject GW; d) Subject YB; e) Subject PM. Detection thresholds are plotted as the far left data point.

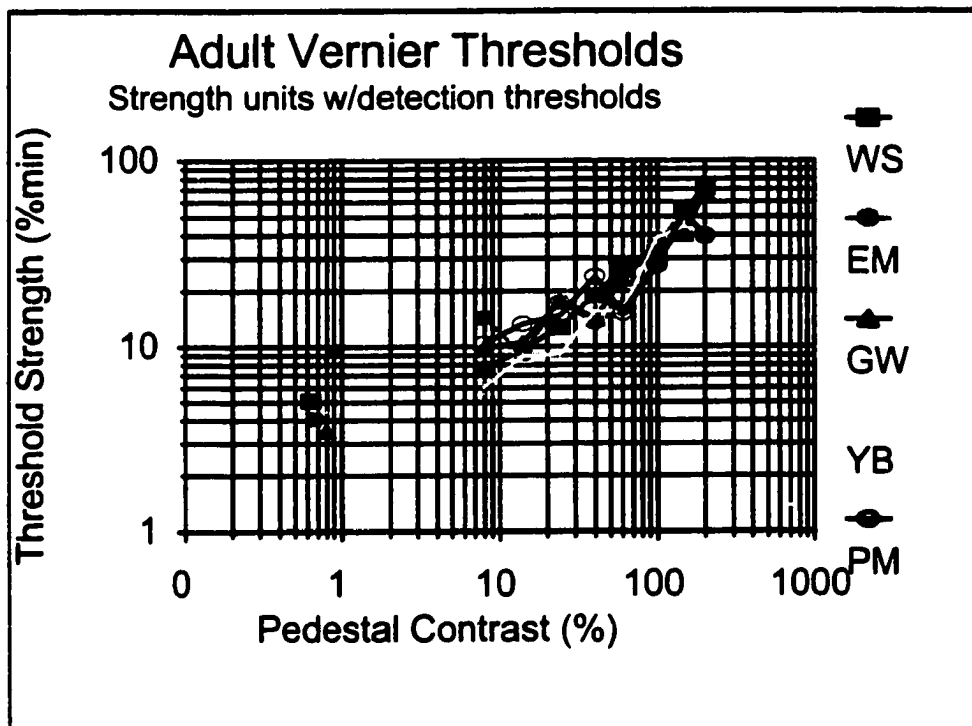


Figure 13

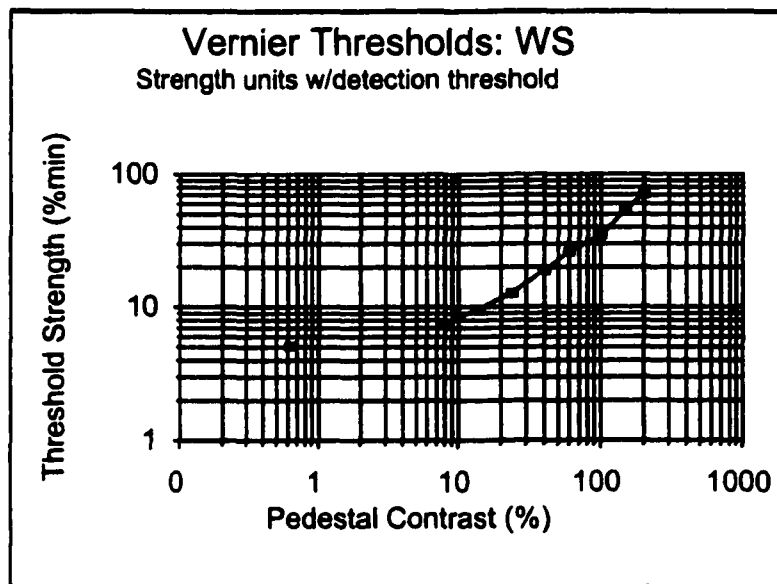


Figure 14a

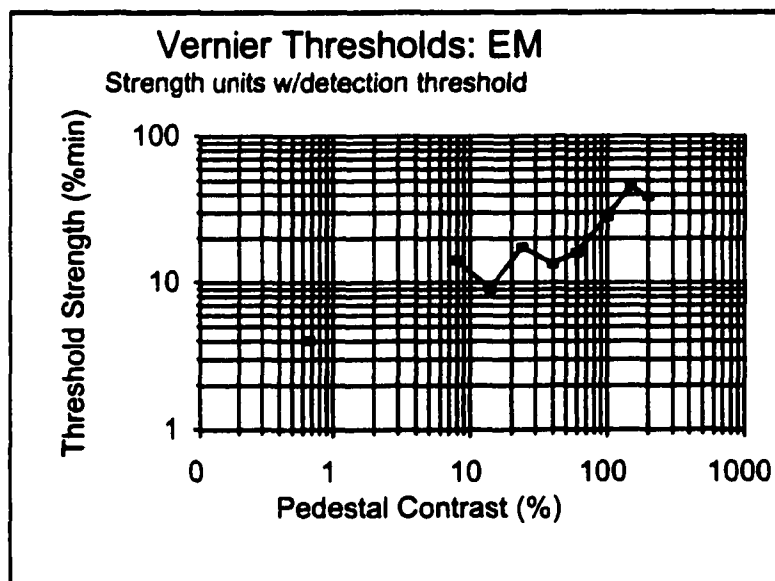


Figure 14b

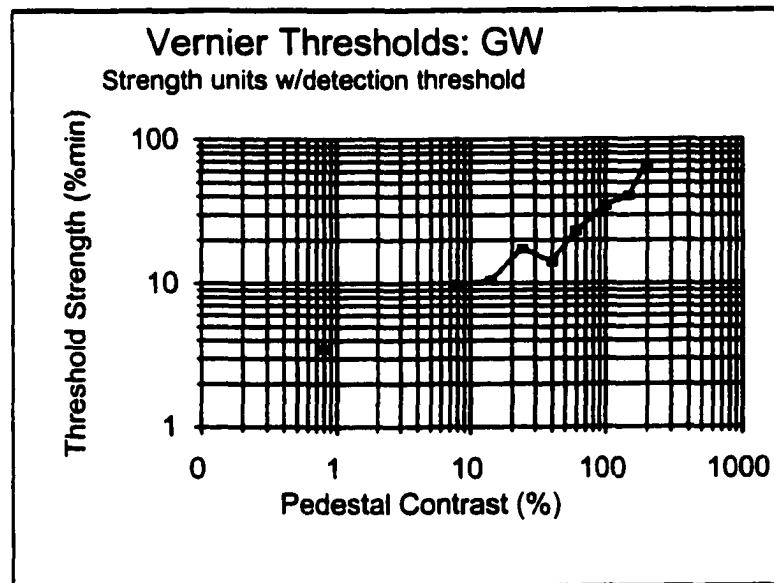


Figure 14c

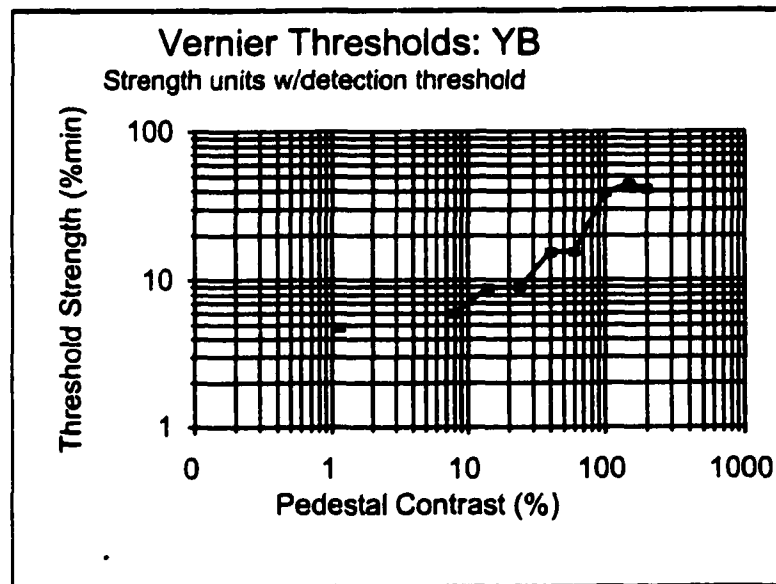


Figure 14d

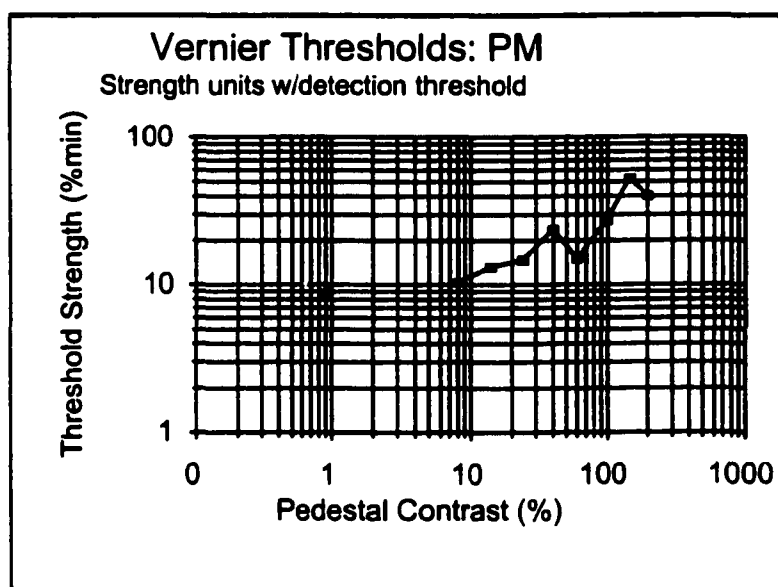


Figure 14e

[4]

DISCUSSION

The results of the detection tasks are what we expected, with lower thresholds for the pedestal edge than for the test line. They are similar enough to the results of previous studies (Klein et al., 1990a, Levi et al., 1994a) to reassure us of both the technique and our implementation of it.

The vernier results further assured us that changes in the methodology for use with infants did not adversely affect this approach. Although individual results are important, it can also be useful to look at the results of the adult subjects as a group. We found that the average test detection threshold (in terms of strength units) was 5.23 %min. Compare this to the average vernier threshold for our lowest contrast condition (8%), which was 9.56 %min. This average test detection threshold is still within a factor of two of the low contrast vernier threshold, as it was with Klein's subjects. Like Klein's subjects, the line becomes harder to detect (in the vernier task) when the pedestal contrast is more than about ten times its own detection threshold. Our subjects performed similarly to those of Klein et al. (1990a) with the exception of two subjects. For the two subjects whose data was not similar to the others, there are a couple of things which should be noted. To begin with, EM and GW were the only two female subjects and they were also the youngest subjects. Although there is nothing to indicate that gender may have an effect on vernier acuity (although see Gwiazda et al., 1989), it is possible that the age of these subjects played a role in their different performances. Their age might have played a role not with

respect to visual development, which is thought to be fully mature by this time, but rather with respect to experience and training. However, both of the female subjects in this experiment were as highly trained as the male observers, so we must rule out experience as a reason for these differences.

Another important aspect to look at is the change in function when the data are transformed into strength units. Rather than seeing a decrease in threshold with increased contrast, we see an *increase* in vernier threshold. This is taken as an indication that the pedestal is actually *masking* the test as pedestal contrast gets stronger. This is similar to results seen in a totally unrelated study by Limb and Tulunay-Keeseey (1981). They demonstrated that an edge caused masking of a line stimulus as it moved closer to the edge, hence hindering its detection and increasing threshold. This is analogous to what is happening in this experiment; detection of the test (in the vernier task) becomes more difficult as the masking of the pedestal contrast becomes stronger.

The results of this first experiment indicate that not only is the test-pedestal approach replicable, but it is still usable even with changes made to allow for infant testing.

[5]

EXPERIMENT #2 - INFANT DETECTION

EXPERIMENTAL DESIGN AND METHOD

In this experiment, we measured the detection thresholds of the test (lines) and pedestal (edge) for infant subjects. The stimulus configurations and procedures were similar to those that were used with our adult subjects, with some minor adjustments for use with infants. For example, although the stimulus configurations were the same, the viewing distance was changed in order to scale the size appropriately for infants. We also chose a higher contrast starting point, expecting that infant thresholds would be higher than those of adults. Additionally, the procedure was slightly different for infants. This is because although adults can make and record a decision on their own, the same cannot be said of infants. Therefore it was necessary to have an observer make a decision about stimulus placement based on infant behavior rather than being able to rely on the infant to make their own judgement.

5.1 Subjects

For the detection experiment, thresholds from a total of 15 different infants were measured, some of the infants contributing to more than one threshold. They were 4-6 months old, with a mean age of 172.9 days and a standard deviation of 14.5 days²; 5 infants were female and 10 were male. Although the technique used to determine threshold, two-alternative forced choice preferential

²

One infant came into the lab at two different ages, so her age and gender have been counted twice to calculate an appropriate average.

looking, works well with younger infants (e.g. 3-month-olds), pilot testing indicated that 5-month-olds responded better to these tasks. Infants participated through the Infant Study Center of Brooklyn College, where the refractive and accommodative status of each infant were assessed using paraxial photorefractometry as part of a screening procedure (Abramov, I., Hainline, L., & Duckman, R.H., 1990). Paraxial photorefractometry is a technique used to assess refractive power and accommodative ability; it is quick and unintrusive, which makes it ideal for use with infants. Its premise is based on the amount of light reflected out of the eye's fundus when photographed with a camera and flash while the subject looks at self-illuminating targets at various set distances. This allows for a qualitative assessment of refractive and accommodative development. This technique was used as a screening device to rule out infants with anomalous vision. Photorefractometry results for three infants were unusable due to equipment failure, but pediatric examination revealed no reason to suspect anything other than normal visual development. Infants with either extreme myopia or hyperopia, strabismus or anisometropia were excluded from the database. Infants who participated more than once within a two-week period were not photorefracted a second time. Each infant contributed to one or more thresholds, depending on their state at time of testing. Data at the end of a session were discarded if the infant either didn't complete the task or was judged subjectively to be too distracted or distressed by the observer. Fully informed consent was obtained from the parents prior to testing.

5.2 Stimuli

5.2.1 Pedestal Stimulus (Edge).

As explained in Experiment #1, use of an edge as the pedestal instead of a line was preferable because of increased generalizability with an edge and the belief that it would be more attention-grabbing to infants than a line. Previous infant vernier research (e.g. Skoczenski & Aslin, 1992) has indicated that 37 cm is an appropriate viewing distance for these types of tasks, so this was the distance set for all of the infant studies. This produced an edge pedestal that subtended 12.37 degrees of visual angle. The height of the edge extended the whole height of the screen, which was 20.1 cm, subtending a vertical visual angle of approximately 28.5 degrees at the 37 cm viewing distance.

As with adults, contrast of the edge was determined using Equation 1. The stimulus configuration was exactly that with which adults were tested (see Figure 4). That is, one side of the screen contained a pedestal and an adjacent lighter rectangle, while the other side of the screen was a uniform field. This helped to insure that even if the pedestal contrast was increased or decreased, the two sides of the screen remained the same in space averaged luminance. This prevented infants from discriminating between the sides based on luminance rather than contrast. As with all of our multipoles, our interest was in the strength of the edge, not just its contrast. Contrast sensitivity was multiplied by 100 to produce the strength of the edge, in units of percent.

5.2.2 Test Stimulus (Line).

The test stimulus (line) was composed of two lines (see Figure 5), rather

than the single line used by Klein et al. (1990a). As explained previously, this was because our vernier task had an edge with two offsets rather than just one. This was done in order to create a stimulus which was more attractive to infants. To be true to the test-pedestal model, therefore, this necessitated a test stimulus which contained two lines as well.

As with adults, it was important that the width of the test lines fall within the spatial summation area. A review of the literature (e.g. Hamer & Schneck, 1984; Brown, 1988; Hansen, Hamer, & Fulton, 1992) has produced many estimations, but these have been done generally under scotopic conditions, have used different stimuli (usually a spot rather than a line), and were tested with different age infants. However, since Ricco's area for infants was not measured explicitly in this study, we used these estimations as an approximation for our stimuli. For example, Hansen et al. (1992) measured spatial summation in infants and found a mean diameter of 2.67 deg (with a standard deviation of 0.64 degrees) under light adapted conditions. We used lines that were 10 pixels wide, which subtended 28.98 minutes at a viewing distance of 37 cm, believing this to fall within Ricco's area for infants. The length of the lines was also important, because we needed lines which were long enough for asymptotic performance in the vernier task. Vernier performance as a function of line length has not been previously tested with infants, so we had to estimate an appropriate length. Each of our lines vertically subtended a length of 7.60 degrees at 37 cm, which we believe was long enough for performance to plateau. The two lines were positioned so that one was directly above the other,

and they were vertically separated by 7.60 degrees.

Contrast of the lines was calculated in the same fashion as it was for adults (Equation 2). Again, we transformed the sensitivity of the line into a measure of line *strength* by calculating the product of the contrast (in percent) and the width of the line (in min arc), producing a result in units of %minutes.

5.3 Procedures

The procedures are the same as those used with adults, with adjustments made for infants. A complete description of the procedures may be found in Section 2.4. All stimuli and experimental procedures were generated using the same apparatus as in the first experiment; a more detailed description of the apparatus appears in Section 2.3.

[6]

RESULTS

Although fifteen different infants contributed to the twenty thresholds that were measured for the test and the pedestal, some infants contributed to more than one threshold. Nine infants contributed to the ten test thresholds which were measured, because one infant was measured on two different occasions; three of the infants were female and six were male. The average age of the infants contributing to the group test threshold was 168.7 days, with a standard deviation of 13.2 days. Ten infants contributed to the ten pedestal thresholds, four female and six male. The average age of the infants contributing to the group pedestal threshold was 172.8 days, with a standard deviation of 16.7 days. There was no significant difference between the groups with respect to age, an important parameter to check, given how much vision changes over the first year of life.

We used a 2-up 1-down staircase method with eight reversals to measure a 71% geometric mean threshold. However, because of the length of testing, infants tended to become distracted or fatigued towards the end of a run. Because of this, although we measured eight reversals, we decided to calculate the geometric mean from the first six reversals to determine threshold. Thresholds from six reversals were less variable and gave us more reliable information than four reversals. Figures 15 and 16 are graphs of the contrast detection thresholds for the test and pedestal, respectively. These graphs are plotted in the traditional units of contrast on log axes. Figures 17 and 18 show

Figure 15. Individual infant contrast detection thresholds for the line (test) stimulus, plotted in contrast units.

Figure 16. Individual infant contrast detection thresholds for the edge (pedestal) stimulus, plotted in contrast units.

Figure 17. Individual infant contrast detection thresholds for the line (test) stimulus, plotted in strength units.

Figure 18. Individual infant contrast detection thresholds for the edge (pedestal) plotted, measured in strength units.

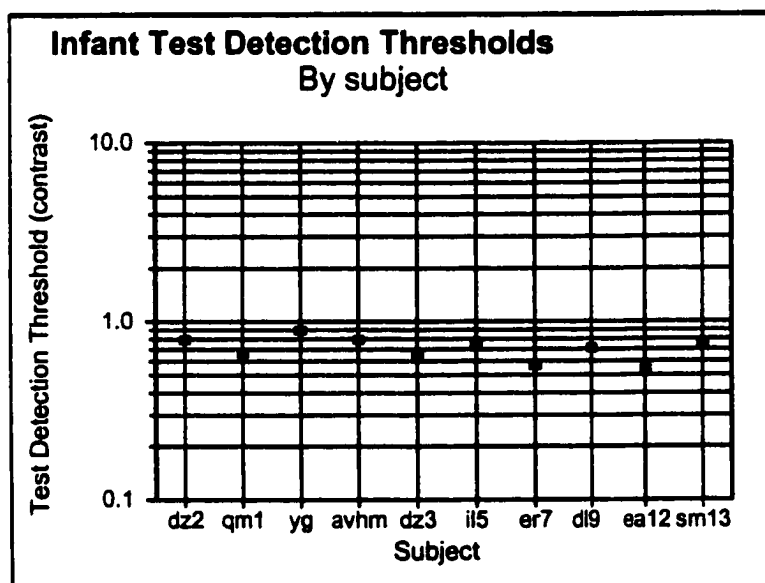


Figure 15

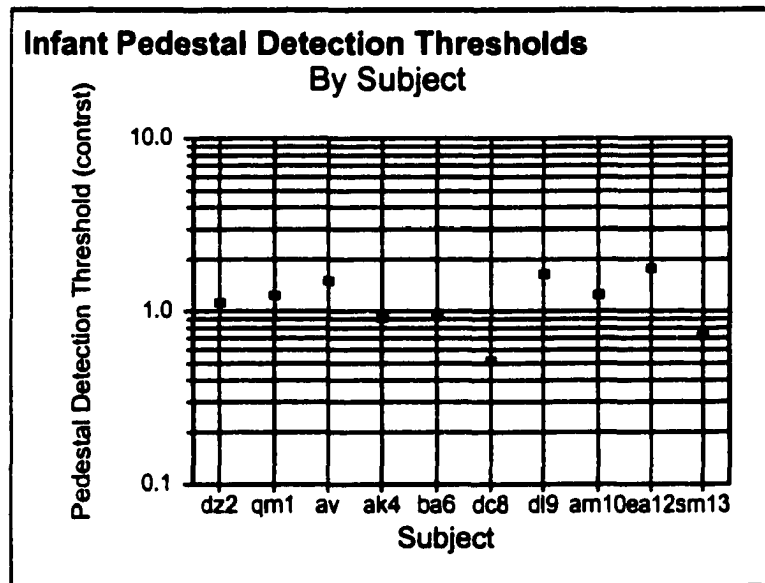


Figure 16

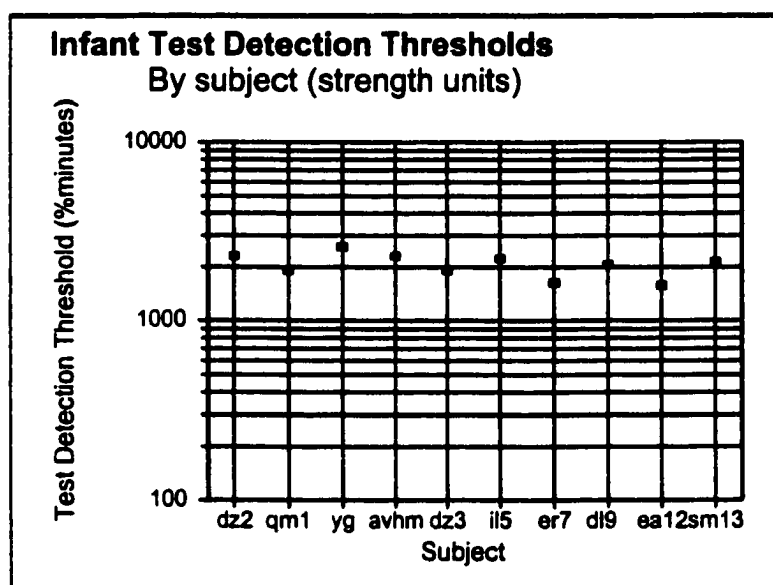


Figure 17

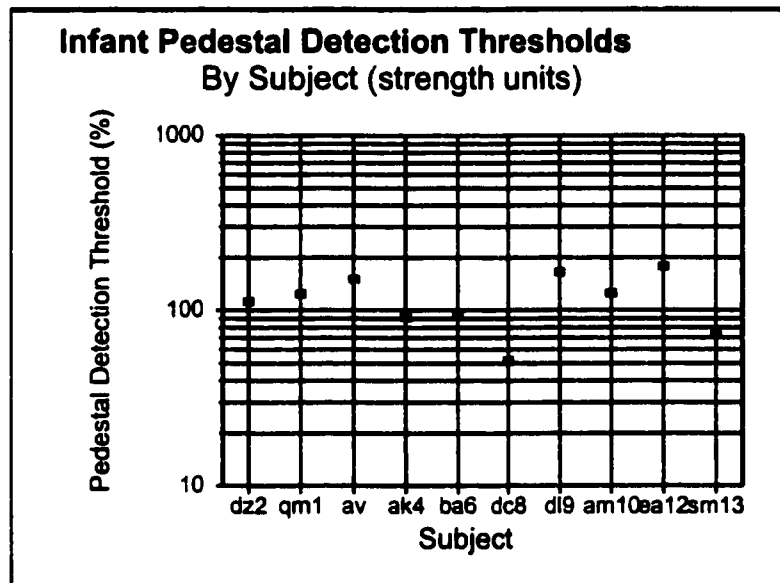


Figure 18

the same thresholds, however, they have been transformed into strength units and plotted by subject on log axes. The transformation into strength units was accomplished in the same fashion as with the adults. The strength of the edge was its contrast threshold multiplied by 100 to produce a measure of percent. The strength of the line was determined by the formula

$$S_T = C_T \times \Delta \times 100\%$$

where C_T is the contrast threshold of the line and Δ is the width of the line, resulting in units of %minutes. By examining them, one can see two unexpected findings. Most surprising, we found that the average pedestal threshold was *higher* than what we obtained for the average test threshold. The average test detection threshold for infants was 0.710, while the average pedestal detection threshold was 1.165. This is startling, given that typically, adults thresholds decrease with increased stimulus size; our adult edge thresholds were much lower than our line thresholds. Additionally, there was much more variability in the pedestal thresholds than in the test thresholds; pedestal thresholds had a standard error of 0.127, while there was a standard error of 0.034 for the test thresholds.

What was not surprising was that both of these thresholds were also considerably higher than those of the adult subjects. The average test detection threshold for infants was 0.710, whereas that for the adults was 0.087. This means that the infant threshold was about 8 times higher than the adult threshold. The average pedestal detection threshold for infants was 1.165, whereas that for the adults was .008. In this case the infant pedestal threshold

was about 140 times higher than that of the adult.

The inflated edge thresholds prevented us from calculating Ricco's area with any degree of certainty. With Ricco's area, it is expected that as line width increases, threshold decreases. This was true with our adult data. Unfortunately this was not the case with the infant data; rather, we obtained lower thresholds for the narrower width stimulus (line). The high pedestal threshold affects the Ricco's extent (z), because the pedestal threshold is used to calculate it, that is

$$z = S_{T_o}/S_{P_o},$$

where S_{T_o} and S_{P_o} are the strengths at threshold of the test (line) and pedestal (edge) respectively. Given a line threshold of 2056.4 %min and an edge threshold of 116.5 %, this would give us a spatial summation area of

$$z = 2056.4\%min/116.5\% = 17.7 \text{ min.}$$

If the pedestal threshold is artificially inflated, as we believe, this is an *underestimate* of the Ricco's area for infants.

[7]

DISCUSSION

The surprising finding that the edge pedestal threshold was higher than the test pedestal threshold forced us to examine our stimuli more closely. We had originally believed that use of an edge in a detection task would be attractive and therefore easily measurable in infants. However, the elevated thresholds appeared illogical, given that detection thresholds generally decrease as line width increases, at least with adults. It is possible that infants could behave differently from adults, but other reasons make this hypothesis untenable. For example, in subsequent testing infants were able to perform low contrast vernier acuity tasks with stimuli which were constructed with these edges. It would be unreasonable for infants to be able to perform a vernier acuity task with edges if they were unable to detect them. Also, anecdotally there were indications that the edge pedestal may not have been especially interesting to infants. Initially infants looked at the stimulus and then seemed disinterested very quickly, much more quickly than during the test detection task. It seems to be a reasonable hypothesis that the high thresholds were due to the unattractiveness of the edge stimulus. Our results appear to indicate that something other than the sensitivity of the infant visual system was being measured.

In order to investigate this finding the first thing we did was to examine the trends in the data. Boredom or unattractiveness could be indicated by a decrease in threshold for the beginning reversals, followed by an increase in threshold for the later reversals. Specifically, we were looking for a lower

threshold with the first two reversals, compared with later reversals. This is in fact what was found; for most infants, threshold was at its lowest with two reversals and then increased with four and six reversals (Figure 19). This may indicate that infants could indeed see the stimulus but were bored quickly by it.

The second thing we did was to run another experiment measuring detection thresholds for two other stimuli, one of which was narrower than our original test stimulus and one of which was wider than our test, but narrower than our pedestal. We predicted that infants would have the highest thresholds for the narrowest stimulus and the lowest thresholds for the widest stimulus and that the test thresholds for our original stimulus would fall somewhere in between. Thresholds for the edge pedestal would be, on average, higher than the line thresholds. Taken together with the data trends, we believed this would give credence to our hypothesis that the edge pedestal was simply and unattractive stimulus. A more detailed description of that experiment may be found in Chapter 11; its results are presented in Chapter 12.

Figure 19. Individual infant edge detection thresholds for 2, 4, and 6 reversals. The geometric mean is plotted for each set of reversals.

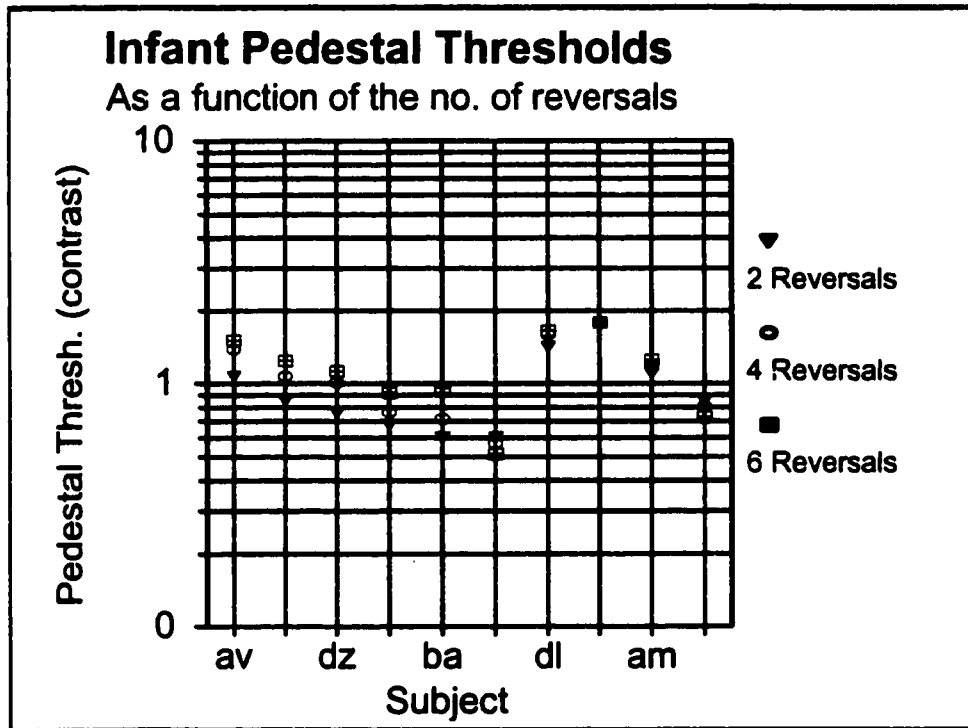


Figure 19

[8]

EXPERIMENT #3 - INFANT VERNIER EXPERIMENTAL DESIGN AND METHOD

In the second infant experiment we measured the vernier acuity thresholds of infants at 4 different contrasts, which, using the multipole approach, are twice the Michelson contrast: 20%, 40%, 100% and 200%. This was done in order to see whether the detection thresholds of the test and pedestal could be used to predict performance on a vernier acuity task. It was also done to examine the effects of contrast on vernier performance in infants. It is clear that as contrast decreases, hyperacuity thresholds increase for certain types of tasks; edge and line vernier are two tasks that are contrast-dependent. However, although it might seem logical to assume that this effect is similar in infants, it has not been measured empirically.

8.1 Subjects

Nineteen 4-6 month-old infants with a mean age of 172.9 days and a standard deviation of 16.9 days participated in this study. Five infants were female and 14 infants were male. Subjects were solicited through the Infant Study Center of Brooklyn College, where they also received free visual screening. As in the detection experiments, each infant's refractive status was assessed using paraxial photorefractometry as part of the testing procedure. Photorefractometry was a useful device to rule out infants with anomalous vision, such as extreme myopia or hyperopia, strabismus or anisometropia. Data from infants who had any of these conditions were excluded from the analysis.

Infants who participated more than once within a two-week period were only photorefracted once; infants participating again after two weeks were photorefracted a second time. Infants were tested in as many different conditions as their comfort allowed; some infants contributed only one threshold, whereas some infants contributed as many as four thresholds. One infant contributed five vernier thresholds over two visits.

8.2 Stimuli

The vernier stimulus was an edge with an abutting vernier offset (see Figure 6), created by adding a line (test) to the edge (pedestal). As with the adults, we actually added two lines to the edge to create two vernier offsets along its extent. For the same reasons as mentioned previously, this was done in order to increase attractiveness to the infants because it added more contours for the infants to examine. Multiple contours have been shown to be more interesting to infants than straight lines (Skoczenski & Aslin, 1995). This has been an underlying premise for any infant research done with a vernier stimulus, that infants prefer looking at a line with an offset rather than at a plain line. This is true for grating stimuli as well; offsets create a more visually interesting stimulus. As with the edge pedestal, contrast of the vernier stimulus was determined using Equation 2. The viewing distance was 37 cm, as it was in all of the infant testing, creating an edge pedestal that subtended 12.37 degrees. The height of the vernier stimulus extended the height of the screen, which was 28.5 degrees at this viewing distance.

8.3 Procedures

Vernier testing was accomplished in the same manner as with adults; for a more detailed description of the procedures, refer to Section 2.4; for the apparatus, Section 2.3.

[9]

RESULTS

Vernier thresholds were measured as a function of contrast for four different contrast levels: 20%, 40%, 100%, and 200% (approximate log increments). Table 4 lists the average vernier thresholds over all contributing infants for each contrast condition. As we examine the thresholds, the first thing to notice is that thresholds seem somewhat high; they are much higher than the Nyquist limit, begging the question of whether they should even be called hyperacutities. In addition, these thresholds are higher than those of other infant studies. However, until the present research, infant vernier acuity has never been measured using an edge as the vernier stimulus. Other studies obtaining thresholds as low as 25 arc minutes have used motion in their procedures as well as line or grating vernier stimuli. It is likely that even if motion detection was not confounded with vernier discrimination, the dynamic properties of the stimuli increased infant interest; indeed, that is why motion was utilized in the first place. The highest threshold obtained with static stimuli (44 arc min) has been in a study by Skoczenski & Aslin (1992) who used a single bar as the vernier stimulus. This is lower than our lowest threshold, but it seems very possible that our use of an edge for the vernier stimulus diminished infant attention, as it did in the detection task. Since it had proven to be an unattractive detection stimulus, it stands to reason that it was not very appealing as a vernier stimulus, either.

Another thing to examine are the standard errors of the data. Although the size of the standard errors indicates a great deal of variability, which is typical

Table 4

Infant Vernier Thresholds Under Four Contrast Conditions.

Infant vernier acuity was measured under four contrast conditions. The average age of the infants tested was 172.9 days, with a standard deviation of 16.9 days.

	Contrast			
	20%	40%	100%	200%
Average (min)	105.6	106.9	75.6	74.8
SEM (min)	16.0	16.2	4.0	13.0
N (points per threshold) ^a	10	10	10	10

^aNineteen infants contributed to the thresholds that were obtained, with infants contributing as many thresholds as their state allowed.

with infant data, there is a surprisingly small amount of variability for the condition when the stimulus is at 100% contrast. Based on adult performance, it seemed obvious that the 200% contrast condition should generate the lowest threshold with the least amount of variability, but this was not the case. Although the threshold was lowest, it was only slightly smaller than that of the 100% contrast condition, with much greater variability. From observation we believe that the 200% contrast appeared somewhat unsettling to the infant; the room was dark and they were located very close (37 cm) to the screen. The brightness seemed ever so slightly aversive, whereas we did not observe this at all with the 100% contrast stimulus. It appeared as if the 100% contrast stimulus had contrast that was sufficiently high enough to attract attention, but was low enough not to be jarring.

In addition and unsurprisingly, infant thresholds were also much higher than those of our adult subjects. The trend of the data, however, was very similar to that seen with normal adults. Infants show contrast dependence in this task, with higher thresholds at lower contrast and lower thresholds with increased contrast (Figures 20 and 21), although the data are noisy. Furthermore it is interesting to examine the slopes of these vernier functions. When plotted in traditional units (Figure 21), the slope of the curve is -0.18 , which is very flat; when transformed into strength units (Figure 22), the function has a slope of 0.82 . In contrast the slope of the adult data was 0.56 in strength units. When the data are transformed into strength units, the slope and direction of the function change; rather than decreasing with contrast, thresholds actually

appear to *increase* with increased contrast. This is because we are now viewing the same data through a different perspective, i.e. detection of an offset in the presence of a masking pedestal. Klein views the transformed data and their function as a way to determine how much detection of the offset is masked by the pedestal. This much steeper slope for the infant function indicates that the pedestal may have caused a greater deal of masking for the infants than for the adults.

When the results of our adults were plotted, we were also able to plot an additional data point. When plotted in traditional units of minutes, we were able to plot Ricco's area for each adult subject, by calculating Ricco's area with the previously explained formula

$$z = S_{T\sigma}/S_{P\sigma}$$

and using the pedestal contrast (in percent) for the abscissa. Although calculated using strength units, the resulting summation area is in minutes of arc and can be plotted alongside the traditional vernier function. Unfortunately, this was not possible with our infant results. Because of the spurious thresholds obtained with our edge pedestal, we were unable to appropriately calculate Ricco's area for our infant data. The edge detection threshold is used to determine both the ordinate and the abscissa, making it unusable for these purposes.

If we examine the next graph (Figure 22), which transforms and plots our results in strength units, we come up against the same problem, but with one redeeming result. In this graph, the additional point that we'd like to include is

Figure 20. Scatterplot of individual infant vernier acuities.

Figure 21. Mean infant vernier thresholds plotted in units of minutes of arc. The disconnected point is the calculated Ricco's area for infants, with the pedestal detection threshold as the abscissa. The unlikely results of the infant edge detection thresholds makes this point questionable.

Figure 22. Mean infant vernier thresholds plotted in strength units. The disconnected point is the test detection threshold; the abscissa is the pedestal detection threshold. Note that although the location of the point along the abscissa (based on the edge detection threshold) seems to be inflated, and therefore the shift along the axis is questionable, the results of the test detection (ordinate) do not appear to be inflated. Notice that this ordinate is close to the lowest contrast vernier threshold.

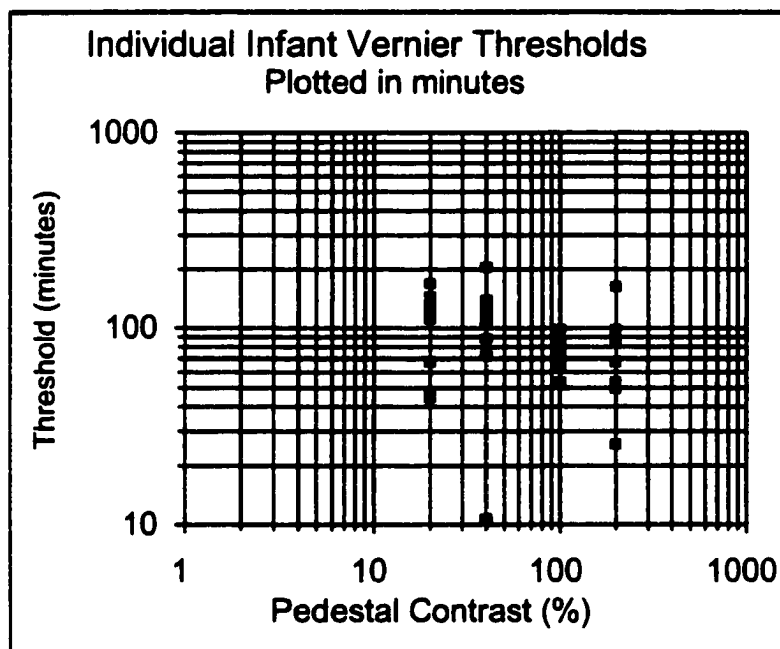


Figure 20

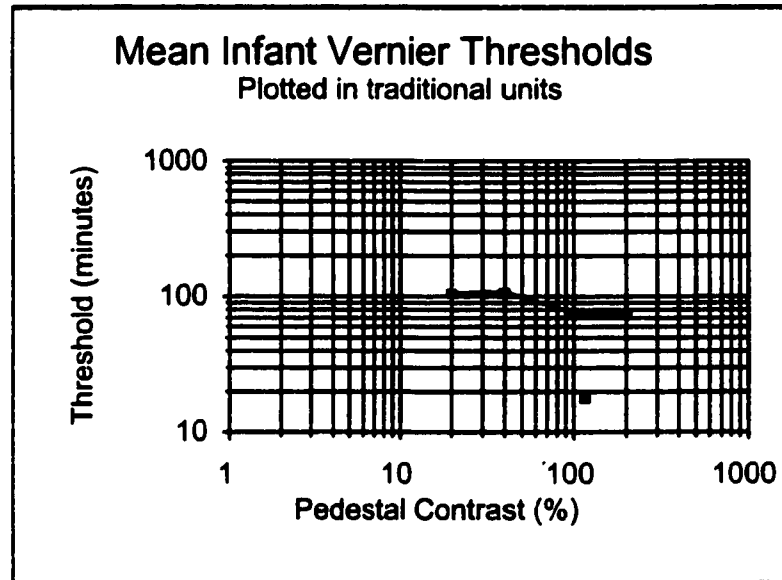


Figure 21

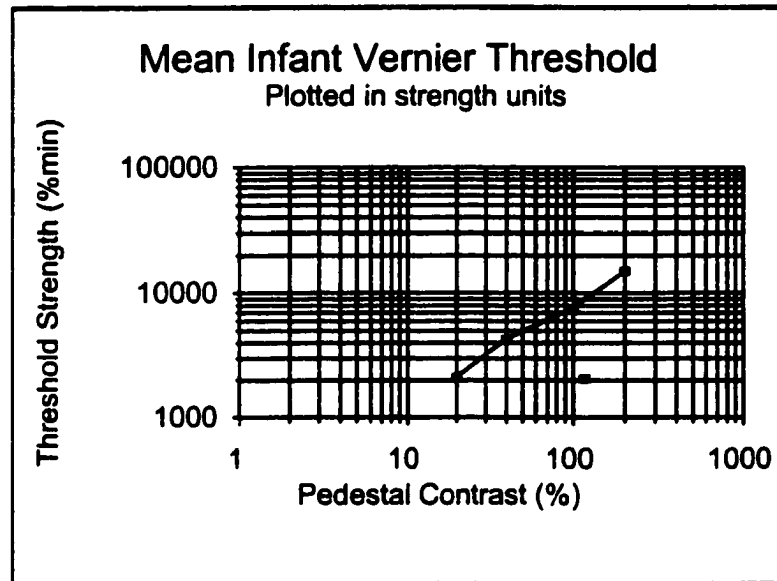


Figure 22

that of the detection thresholds. This point uses the test detection threshold as the ordinate and the pedestal detection threshold as the abscissa. This point is shifted along the abscissa by an amount that seems unsuitable (because of the inflated pedestal threshold), but we have no reason to question the appropriateness of the ordinate. The test detection threshold (2056%min) is very close to the 20% contrast vernier threshold (2111%min), which might indicate that the test could be used as a predictor of vernier performance. However, there are at least two problems associated with this conclusion. First, the lowest contrast at which we measured vernier acuity was 20%. This does not necessarily mean that this is the threshold contrast for infants; it's simply the lowest contrast that we measured. If we had measured vernier acuity at a lower contrast we may have arrived at a different threshold which would not have been in such close agreement with our test threshold. Second, the width of the lines chosen for the test stimulus was not necessarily within Ricco's area. This clouds its ability to be used as a predictor of vernier performance.

[10]

DISCUSSION

We can reasonably conclude from this experiment that edge vernier acuity is contrast-dependent in infants, as it is with adults. And while it may be tempting to conclude, therefore, that underlying contrast mechanisms in infants are similar to adults, it would be premature to do so based on this data. We cannot say that the mechanisms underlying infant vernier acuity are similar to those of adults because the slopes of the infant data are so different from the slopes of the adult data. However we can see that these mechanisms are immature in the 5-month-old and that it is difficult to distinguish between visual and cognitive (i.e. attention) capabilities in infants.

Although the results are too uncertain to claim its use as a predictor, we do see that when transformed into strength units, the mean test detection threshold is similar to the mean low contrast infant vernier threshold. This might be taken tentatively as an indicator that visibility of the test, as defined by the test detection threshold, may be a limiting factor for infant vernier acuity, as it is in normal adults. Additionally, we found that when transformed into strength units, the slope of our infant data was much steeper than that of our adult data. Klein et al. (1990a) take the slope of the function as a measure of the amount of masking that the pedestal enforces on the test. A shallow slope is viewed as less masking than a steep slope. Our steep infant slopes would therefore indicate that the edge has a very strong masking effect on the test.

[11]

EXPERIMENT #4 - INFANT DETECTION REVISITED**EXPERIMENTAL DESIGN AND METHOD**

In this experiment, we sought an explanation for the results of the edge detection experiment. In Experiments 2 and 3, we measured the infant detection and vernier thresholds for our multipole stimuli, a line and an edge. We found that the sensitivity of the test (line) was in close agreement with the vernier threshold at low contrast. We also found that, with respect to contrast and vernier acuity, infant performance follows a similar, albeit shallower, trend to that displayed by adults. That is, infant thresholds increase with decreasing contrast; they are contrast-dependent as in the adult visual system. However, we were faced with the problem of the pedestal threshold; it was much higher than was expected. In fact, it presented us with an interesting paradox: infants could perform vernier acuity with edge stimuli that in the detection experiments seemed to be undetectable, although the point could be made that in actual fact detectability of the edge is unnecessary to perform the vernier task. Also, the data were totally contrary to adult performance, which demonstrates that as the width of the line increases, threshold decreases until it asymptotes at a low level (see Figure 23). Detection of the pedestal should have given us a point in that asymptotic region parallel to the abscissa, but instead it gave us thresholds that were higher than our thin line stimulus (see Figure 24). This result seems to indicate that the test-pedestal model is not appropriate for use with infants, at least with the edge stimulus as the pedestal. Alternatively, since Ricco's area

Figure 23. Adult detection thresholds as a function of line width. Notice that as the line width increases, thresholds decrease and then appear to asymptote.

Figure 24. Infant detection thresholds as a function of line width for the 0.50 degree line (test) and the 12.37 degree edge (pedestal). Notice the increase in threshold for the wider stimulus.

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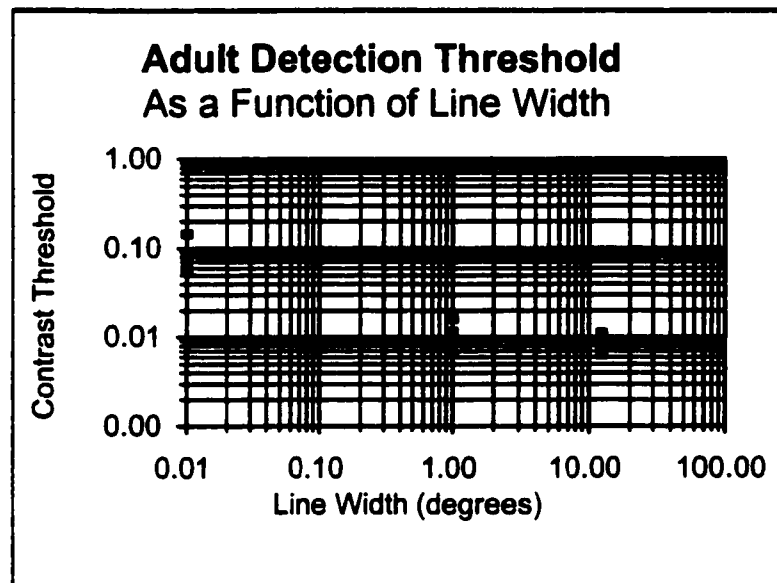


Figure 23

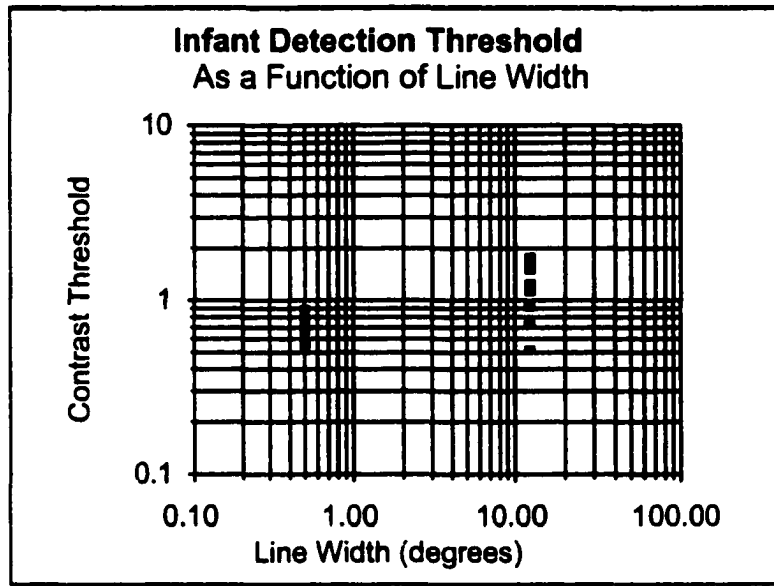


Figure 24

was not explicitly measured, it is possible that the widths of the multipoles chosen were not appropriate.

During testing it seemed to us that the pedestal (edge) stimulus was not a very interesting stimulus. We believed that this was one reason that our vernier acuities were so high for these stimuli; an edge is just not very attractive to an infant. It also appeared that having more than one stimulus, as we did with the thin lines, was more interesting than one long uninterrupted block. In order to test the attractiveness hypothesis, however, we needed to do two things. One was to examine the trends in the data for the pedestal detection thresholds. Finding the stimulus unattractive could be indicated by a lower threshold for the beginning reversals than for the later reversals. This was indeed the case, as mentioned in the results on infant pedestal detection, in Experiment #2. The other important thing to do was to measure other line widths in order to determine what the line width vs threshold function looks like for infants. With adults we know that as line width increases, threshold decreases until it reaches a plateau. With infants we surmised that at very thin widths, the test detection threshold would be very high; as the size of the lines increased the threshold should decrease. Based on our edge detection results we would then infer that as the size of the line got too wide (and became an edge) thresholds would rise again. The relationship with line width and threshold is what we tested in this last experiment. We measured detection thresholds for two additional stimuli, a 1.0 degree line and a 0.24 degree line, with the same configuration as the test stimulus. The 0.24 degree stimulus was narrower than our original test stimulus

and the 1.0 degree line was wider than our original test stimulus, but narrower than our edge stimulus. We expected that we would get higher thresholds for the 0.24 degree line than for our original test stimulus because it was narrower. We also hypothesized that we would get lower thresholds for the 1.0 degree stimulus than for any of our previous stimuli, because we believed that increasing the width would make the stimulus more easily detectable for the infants while avoiding the unattractiveness of the edge. This would show that attractiveness of the stimulus was confounding the detectability of the edge stimulus. These results would indicate that while an edge as a pedestal may not be useful with infants, a different pair of multipoles, e.g. a line and a dipole, could be used effectively. Although our original thinking was that infants might find an edge more attractive because it would create a larger area of contrast difference, it seems that an edge is so large as to be boring.

11.1 Subjects

Seven infants from the Infant Study Center were tested with these stimuli, 4 females and three males. The average age of the infants was 181.7 days, with a standard deviation of 27 days. One infant had been tested with these stimuli prior to the experiment but her data were excluded because she was under age (100 days). Infants contributed as many thresholds as their comfort and attention allowed. All infants were photorefracted with the technique described in the previous experiments, in order to screen for anomalous vision.

11.2 Stimuli

For this experiment we measured detection thresholds for lines that were

0.24 degrees wide and lines that were 1.0 degree wide at 37 cm viewing distance. The length of the line remained the same as in the first experiment, vertically subtending a length of 7.60 degrees. As in the previous test detection experiment, two lines were used for each test stimulus rather than the single line of Klein et al. (1990a) because this was more similar to our vernier stimulus, which had two offsets and not just one.

One caveat must be noted. In order to increase the attractiveness of the stimulus, we decided to use the configuration of the test stimulus (rather than that of the pedestal stimulus), which was created by positioning two lines one directly above the other with a separation between the two. This means that the stimulus was altered in two dimensions, in both the width and the configuration. It is possible that had we just changed the width this would have also increased the attractiveness of the stimulus and decreased its threshold. However, during testing the test configuration seemed appealing to infants, even with a very thin line. Therefore we altered both the width and the configuration in order to optimize the attractiveness of the stimulus.

Contrast of the lines was determined in the same fashion as the original experiment, using Equation 1. As before, we measured the *strength* of the line, strength being determined as the product of the contrast (in percent) and the width of the line (in min arc), and therefore was in units of %min.

11.3 Procedures

Following the same methods as in our previous experiments, we used a two alternative forced preferential looking procedure to measure infant

thresholds. For a more detailed description of the apparatus and procedures, refer to Sections 2.3 and 2.4.

[12]

RESULTS

We tested 7 infants with the new stimuli and obtained 4 threshold points for the 0.24 degree line and 6 thresholds for the 1.0 degree line. Combining these data with our previous data provided us with contrast detection thresholds for a total of 4 line widths: 0.24, 0.48, 1.0, and 12.37 degrees (see Table 5). All of the data are plotted on log axes in Figure 25. Although the slope is shallower than that seen for adults (-.02), the same downward trend is indicated in the data as the width of the stimuli increase from a 0.24 degree stimulus to a 1.0 degree stimulus. A one-way analysis of variance indicates that the difference between the thresholds approaches significance with $p = 0.07$. These results indicate that there was indeed a decrease in threshold from the 0.24 degree line to the 1.0 degree line. However, one can also see that thresholds for the 0.24 degree line are similar to, even slightly lower than, those for the 0.48 degree line. After the decrease in the thresholds for the line, there is a marked increase in the edge thresholds. There is also a decrease in variability with the increased line width, except when looking at the edge pedestal, which has the highest variability of all the stimuli.

Table 5

Average Infant Detection Thresholds for Experiment 4.

Below are the average infant detection thresholds for all of the detection stimuli. The thresholds for the 0.48 degree line and the edge were measured in the earlier detection experiment. Results are presented in contrast units.

	0.24 Degree Line	0.48 Degree Line	1.0 Degree Line	12.37 Degree Edge
Mean	0.6736	0.7096	0.5582	1.1651
Standard Error	0.099	0.034	0.039	0.127

Figure 25. Infant detection thresholds for the 0.24, 0.50, 1.0 and 12.37 degree stimuli. Notice that thresholds appear to decrease with line width, but then increase for the very large stimulus.

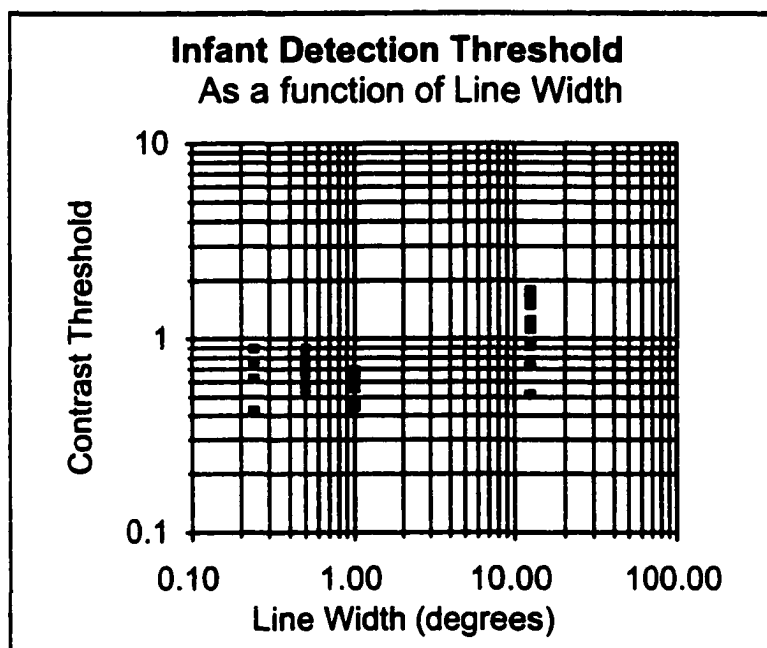


Figure 25

[13]

DISCUSSION

These results indicate two things. First of all, they give credibility to our hypothesis that the high edge thresholds that we originally obtained were more than just a function of poor visibility. Whether because of a change in width or configuration, the stimulus became more attractive and so we obtained lower thresholds. This strengthens our belief that something other than visual sensitivity, e.g. attractiveness or lack thereof, was responsible for the high edge thresholds. Second, with the additional testing of these two line widths, we see the downward slope which is typical of adult data. It is shallower than the adult curve (with the infant slope differing from zero with $p=0.07$) but, like adults, this function shows that detection thresholds decrease with increased line width. Although it seemed reasonable to believe that thresholds for wider stimuli should be lower than those for thinner stimuli, these results empirically demonstrate that. We would also like to be able to determine Ricco's area using these stimuli, however we must conclude that unless several other line widths are measured, it is impossible to be entirely certain at which point the curve plateaus and at which point thresholds start to increase again.

Taken together, these results confirm our suspicions that the edge multipole is not an effective pedestal to test with infants. It is possible that if two higher order multipoles were used to construct the vernier stimulus, such as a dipole for the test and a line as the pedestal, then the test-pedestal approach might have needed no adjustments to fit appropriately. However, it is also

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possible that the assumptions underlying this approach are not met in infants. Lastly, the test-pedestal approach was designed to predict individual thresholds, whereas we have attempted to use them with group data, which may not be appropriate.

[14]

GENERAL DISCUSSION

14.1 Overview of Adult Results

The results of the first experiment essentially replicated the results of Klein et al. (1990a) with a small degree of variability. This allowed us to demonstrate that the test-pedestal technique was replicable, even when the methodology was somewhat different to allow for testing with infants. For example, Klein et al. (1990a) used the method of constant stimuli, whereas we used a staircase method, which decreased the average number of trials needed for a threshold. Our subjects generated between 20–40 trials per datum while their subjects performed 500 trials per point. This decrease in the number of trials also undoubtedly contributed to some of the variability of our data. Furthermore, Westheimer & McKee (1977) emphasize the importance of sufficient testing in order to allow performance to plateau; practice effects are known to be considerable for vernier thresholds. Klein et al. (1990a) also used a rating scale for their decisions while we used the two-alternative forced-choice (2AFC) method. This is because generally it's difficult to get an infant to rate a stimulus. Happily, these alterations did not appear to have a strong effect on our adult results. For three out of the five adults tested, the results were comparable to those of Klein et al. (1990a), although shifted slightly higher. This shift, as well as the performance of our other two adult subjects, was most likely due to our use of subjects who were inexperienced in this task; Klein used subjects who had undergone extensive testing with this task and undoubtedly had reached a

plateau in their performance. The two subjects whose data did not quite fit the model were also our youngest subjects, and the only female subjects. Although we can rule out the effects of experience (both were as trained as the other observers), the possible role of gender is unclear. There were not enough subjects to determine whether there was an effect of gender on the results. Previous research has generally never discussed a gender effect on vernier acuity (but see Gwiazda et al., 1989 for exception), but there is not enough evidence in the present research to rule it out. Despite this, however, our overall results were somewhat comparable to those of Klein et al. (1990a): contrast detection points could be used to predict low contrast vernier acuity thresholds (within a factor of two), transformed vernier thresholds increased with increasing pedestal contrast, and Ricco's area could be determined for these subjects. Also, the slopes of the lines fit to the vernier data were comparable to those of Klein.

14.2 Overview and Comparison With Infant Results

14.2.1 Contrast Detection Thresholds.

The test contrast detection thresholds that we obtained were reasonable, albeit higher and with more variability, than those of our adult subjects. This is not exceptional, given how noisy infant data can be. One of the more curious findings of the study, and of special interest for infancy research, was the average detection threshold of the edge pedestal. We found an interesting phenomenon: that the detection thresholds for the edge were higher than for those of a very thin line. Had the test (line) and pedestal (edge) thresholds been

measured in separate studies this would not have been readily apparent. However, having had the benefit of measuring them within the same series of experiments, we could compare our thresholds. These results run contrary to what would be expected, that detection thresholds should decrease with increased line width. We believed this to be an artifact of infant preference and that the increased threshold was due to the unattractiveness of the edge pedestal. Although infants preferred the high contrast to the low when they were being tested, they appeared to lose interest quickly with this task. This necessitated measuring detection for two other line widths, to determine whether we could obtain lower thresholds with different stimuli. As the results of the last experiment showed, when contrast detection was measured using lines of varying widths rather than edges, lower thresholds were obtained with the wider stimuli. Using these stimuli we attained the typical downward sloping part of the contrast threshold vs line width function. The downward slope as line width increases is what would normally be predicted and led us to believe that something other than visual sensitivity, such as attentiveness, was responsible for the high edge thresholds. It also indicated that the edge was not an effective pedestal to use with infants. The dual issues of attractiveness and non-response are always a concern for infancy research. With infant visual perception the question is never as simple as "Can they see it?". Rather it is several questions: "Can they see it?", "Do they want to look at it?" and "How long do they want to look at it?". It is quite possible that an infant can see a stimulus but finds it too unattractive or, even aversive, to attend to for any length of time. Clearly, this

has the potential to obfuscate our sensitivity measurements. Our edge thresholds appear to be a classic example of this.

14.2.2 Vernier Acuity Thresholds.

Our vernier thresholds were higher in absolute terms than those obtained in previous infant studies. It is possible that this had to do with the particular stimuli which were chosen. Up until the present research, vernier acuity using an edge as the vernier stimulus has never been tested in infants. Earlier studies have commonly used gratings, with or without motion, to test vernier acuity (e.g. Shimojo et al., 1984; Shimojo & Held, 1987; Zanker et al., 1992). Skoczenski & Aslin (1992) used a single line stimulus, without motion, and obtained thresholds of approximately 44 arc min for 3-month-olds. This is much lower than what we obtained; at our highest contrast, which is comparable to the stimuli used by Skoczenski, our vernier threshold was approximately 75 arc min. We believe that this was due in large part to the use of an edge as the pedestal; our high edge detection thresholds indicated that this was not as compelling a stimulus as we had believed it would be. It follows that if infants were not interested in this stimulus for a detection experiment then they may have been less interested in it as a vernier acuity stimulus. However, although absolute thresholds were somewhat higher, the pattern of these vernier results seem comparable to previous studies. For example, Skoczenski and Aslin (1992) point out that whereas grating acuity for 3-month-old infants is 5-10 times worse than adult grating acuity (Banks & Salapatek, 1978; Dobson & Teller, 1979; Norcia, Tyler & Hamer, 1990), infant vernier thresholds are actually 250-300 times worse than

adult vernier thresholds. Although we measured detection thresholds rather than grating resolution, the point still holds; at the highest contrast, average test detection thresholds for infants were approximated 8 times worse than for adults, whereas average vernier thresholds were on average approximately 290 times worse than for our adult subjects.

14.2.3 Contrast Effects.

The effect of contrast on infant vernier thresholds seems to be very similar to the effect seen in adults; that is, infants demonstrate contrast dependence in the vernier task, with thresholds decreasing as the stimulus contrast increases, when measured in traditional units. This is typically found with adults (Morgan, 1991), and indeed is what we found with the adults that we tested. As mentioned by Morgan, not all hyperacuity tasks show contrast dependence; tasks that do not show scale invariance also seem to be contrast dependent. As with any of these tasks, a great deal depends on stimulus configuration. Like a vernier task with abutting lines, this edge vernier task is not scale invariant, and so we would expect it to be contrast dependent, which it was. Concerning infants, this research empirically demonstrates that the effects of contrast on the vernier performance of infants are qualitatively similar to those found in adults. The downward slope with increased contrast was also seen for infants. However, an interesting observation, which may have led to increased thresholds, was that during testing with the 200% contrast vernier stimulus, infants seemed to find it slightly aversive. It is possible that this is because the high contrast seemed very jarring in the dark room, at a close distance to the

screen. The 100% threshold had the lowest variability and indeed seemed high enough to be attractive without being jarring.

The test-pedestal approach actually gives us two ways to look at the same information. If one views the data traditionally, the results are as expected. Vernier thresholds decrease with increased contrast, indicating that we perform better on vernier tasks when visibility is increased. If we transform the data and view it with respect to strength units, then as the contrast of the pedestal is increased, vernier thresholds actually *increase*. Conceptually this makes sense if we view the vernier stimulus as that of an offset line (test) being masked by an edge (pedestal). This is especially apropos if we examine the data with respect to strength units, which are more appropriate for determining perceptual strength (Klein et al., 1990a). If the slopes of these curves are examined, then the shallower slope indicates that there is less masking of the test by the pedestal (Klein et al., 1990a). This function is what Klein demonstrated, and what we obtained, with adults. With infants we get much steeper slopes, possibly implying that the pedestal causes more masking in the infant visual system than in the adult visual system. Klein's subjects also commented that they perceived the edge pedestal as more of a mask than when a line was used as the pedestal. Given infant response to the edge, this seems likely as well.

14.3 What are the relationships among detection, vernier acuity, and Ricco's area for infants?

We posed four questions in the introduction to this research. Our first

question concerned the connection between detection and vernier acuity; would we be able to predict low contrast vernier thresholds for infants from their detection thresholds, as we can with visually normal adults? Although it is premature to make such conclusions from our data, we did find that the mean infant test detection threshold was similar to the mean vernier acuity at our lowest contrast. This is similar to our adult results and those of Klein et al. (1990a), albeit with thresholds shifted much higher to allow for decreased infant contrast sensitivity. However we must bear in mind that this similarity may be due to our choice of 20% contrast as the lowest contrast measured. Even though 20% contrast seems low for infants, it is possible that vernier thresholds could be measured at even lower contrasts and therefore the similarity between detection and vernier thresholds may be more coincidental than anything else.

Additionally we were interested in whether our results were similar to those of the amblyopic visual system, investigated by Levi et al. (1994a). Indeed, if one takes the test detection threshold as a measure of sensitivity of the visual system, infant results were comparable to results found with the anisometric amblyopes tested by Levi et al, (1994a). They found that the ability to predict low contrast vernier acuity from detection thresholds was true when decreased local contrast sensitivity and increased spatial pooling were taken into account. For our infants one can see that there is a large decrease in contrast sensitivity, however the question of increased spatial pooling remains unanswered with our original stimuli. It seems obvious that with infants there is an increase in spatial pooling that would contribute to their performance, but it

cannot be deduced using the edge multipole as a pedestal. Actually, what can be seen is that even if the edge threshold results are spurious, the spatial integration area is larger than that of adults. If our edge thresholds were lower, as would be predicted and were seen in the last experiment, then the integration region would be even larger than we found. So although an absolute measure was not determined, our results indicate that there is increased spatial pooling with infants, which may contribute to their results as it does with anisometric amblyopes. This result, the similarity between infants and anisometric amblyopes, is a little surprising given previous research which indicates that infants are more like strabismic amblyopes than anisometric amblyopes (Carkeet & Levi 1993). Using the test-pedestal approach, strabismic amblyopes needed an extra error, such as irregular and uncertain sampling, to explain their results (Levi et al., 1994a). One would hypothesize this to be the case for infants as well, if infants are believed to be more like strabismic amblyopes. However, in a study that used the test-pedestal technique with strabismic monkeys (Kiorpes et al., 1997), it was found that detection thresholds could predict vernier acuity without the need to postulate an additional error.

The second question was whether the factors limiting detection are the same in the infant as they are in the normal adult. Klein et al. (1990a) have shown, using the test-pedestal approach, that visibility of the stimulus is the limiting factor for vernier acuity in the adult. This may be the case with infants as well. If not simply serendipitous, the close correspondence between infant test detection and vernier thresholds may be an indication that the visibility of the

stimulus is the limiting factor for the infant visual system. When the sensitivity of the system is measured with the same stimuli as those used for measuring vernier acuity, the same limitations may apply to visually normal adults, infants, and anisometropic amblyopes. The idea that detection and vernier acuity are limited by similar underlying mechanisms is bolstered further in a study by Kiorpes (1992). She measured grating and vernier acuity longitudinally in monkeys and suggests that although they show different time patterns of development (as do human infants), both are limited during development by similar mechanisms. As evidence she cites the fact that, for monkeys, both grating and vernier acuity became adult-like at approximately the same age. Additionally, both functions showed development that was related to each other in a systematic way. She concludes that the two functions may be limited by the same mechanisms, albeit in a different way for each. Furthermore, she points out that these limitations may be earlier in the system than supposed. Although vernier acuity has been hypothesized to reflect cortical factors and grating acuity receptor factors, she cites evidence by Banks & Bennett (1988) that suggests that vernier acuity as well as grating acuity may be limited by receptor factors.

Our third concern was the effect of contrast on infant vernier acuity. As mentioned in an earlier section on contrast effects, the infant visual system appears to be comparable to that of the adult; vernier thresholds decrease with increased contrast. However, as also noted, although both adult and infant thresholds decrease with increased contrast, the slopes of the functions are not the same for both groups. This could be due to an immaturity in infant contrast

processing; alternatively it could be due to infant preference problems with the stimuli that were used.

Our fourth point pertains to the connection between detection and Ricco's area. As mentioned previously, thresholds for the edge pedestal seemed to be artificially inflated, probably because of a confounding of perception and attention in the infant. This resulted in an underestimate of the region since the edge strength is used as the denominator for the calculation of Ricco's area. This is what encouraged us to test other stimuli in the last experiment. However, we achieved only partial success from this experiment. We were able to give credibility to the hypothesis that the high edge thresholds were due to a lack of attractiveness of the stimulus. Unfortunately, from this series of experiments we were unable to deduce the whole function of threshold versus line width. It would have been necessary to test several more stimuli with increasing line widths in order to determine at what point the detection threshold plateaus and at what point it starts increasing because the stimulus is too wide to be attractive to the infant. From the stimuli that we tested we were not able to unequivocally determine where the function asymptotes, and therefore we were unable to calculate Ricco's area from the detection thresholds.

A last point must be made when comparing infant and adult results with this paradigm. We used the mean scores from our infant data to investigate vernier acuity because individual infant data is even noisier than grouped data. However the test-pedestal approach was originally designed for predicting thresholds for individuals. This may also limit the paradigm's usefulness with

infants.

14.4 Filter models, the test-pedestal approach, and two levels of processing

Levi et al. (1994) discuss the fact that models to explain hyperacuity are usually based on filters which are sensitive to contrast and orientation, are localized in space and are bandpass in shape (e.g. Klein & Levi, 1985; Wilson, 1986). Levi et al. (1994) suggest that what brings together the filter model and test-pedestal approaches is that the test-pedestal approach gives a measure of the sensitivity of the underlying oriented filters. Levi et al. (1994a) use both the test detection thresholds and the spatial summation area to calibrate the sensitivity of the oriented mechanisms, although they note that Ricco's area only indicates a filter's lowpass characteristics. They believe that the two approaches are complimentary, because filter models are restricted by the sensitivity of the underlying filters, as measured in the test-pedestal approach. In the test-pedestal approach, however, it is unnecessary to make assumptions about filter sizes, shapes or density.

When these underlying filters suffer a loss in contrast sensitivity, we get degraded results such as those seen for anisometropic amblyopes or our infant data. However, strabismic amblyopes and the periphery suffer an extra loss not explained by a loss in contrast sensitivity (Levi et al., 1994). In order to account for this, Levi et al. (1994) hypothesize two stages of processing: a first level, where contrast is processed, and a second level where position information is processed. This would affect contrast detection performance differently from that of vernier acuity. It would also explain the results for normal as well as degraded

vision. Performance for anisometric amblyopes would be limited by the first stage, which processes contrast, but be relatively untouched at the second level of processing. Strabismics, and the normal adult periphery, would encounter processing limitations at the first contrast stage, and then again at the second position stage. Levi et al. (1994) suggest that noise at this second level of processing which affects strabismic amblyopes and the normal periphery could be due to sparse and uncertain receptor sampling at the level of the cortex.

14.5 Areas of Future Research

Although these experiments provided us with some interesting answers, there are still other questions which remain. Explicitly measuring Ricco's area in order to determine the appropriate size stimuli is a crucial step. In addition it would be fascinating to implement the test-pedestal approach using a different set of multipoles, e.g. a line as the pedestal and a dipole as the test. This would address the questions posed by the high detection thresholds of the edge stimulus. It is possible that if the experiment were done with these multipoles then the detection thresholds which were produced would be as expected and all of the relationships obtained with adults would also be obtained with infants. The thresholds obtained using lines as the vernier stimulus could also be compared with other studies which used single bar stimuli (e.g. Skoczenski & Aslin, 1992).

Another configurational issue which Klein investigated with adults was whether the test stimulus should be a half-field white line added to the edge or whether it should be an opposite polarity full field line that added a black line to

one half of the edge and a white line to the other half. He found that this difference in stimulus configuration did not have an effect on the detection task, but it did on the vernier task. We constructed our stimuli as in the first case, by adding a half-field line to the edge. We did not create or test the second configuration possibility so we do not know if the differences that Klein found with adults would hold true with infants as well.

Lastly, Klein (1989) makes a strong argument for the use of multipoles to assess visual function. In general, the use of multipoles as visual performance stimuli is an intriguing idea which could be investigated more fully. This would provide a variety of novel ways to compare performance among different visual systems such as the normal adult fovea and periphery as well as that of the amblyope and the infant. Of course any use of multipoles would have to deal with the same issue as that of the present research, the attractiveness of the stimuli.

The test-pedestal technique has proven to be an intriguing way to simultaneously investigate many things: contrast detection, vernier acuity with untested stimuli, contrast effects on vernier acuity, and spatial summation, as well as the unintended foray into infant preference. The method, as well as the concept of multipoles in general, has potential for use not just with infants but with other populations. As with any research, the test-pedestal approach has provided us with many questions in addition to answers.

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