MODIFICATION OF THE INFANT CONTRAST SENSITIVITY CARD PROCEDURE

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by

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Abstract

Recent attempts to measure spatial vision in infants have encountered serious drawbacks, such as the expense and sophistication of the equipment required, or the time necessary to complete the test. Adams, Mercer, Courage, and van Hof-van Duin (1992) have developed a prototype contrast sensitivity (CS) card procedure which sidesteps these problems, most notably test time. Despite its success, the prototype possesses several limitations which affect the accuracy and the efficiency of the procedure.

In the present thesis, custom software and printing techniques were developed to construct a new set of CS cards which, compared to the prototype, contain four improvements: (1) Larger, more salient test gratings; (2) higher contrast "warm-up" cards in each spatial frequency set; (3) smaller contrast step size between adjacent cards; (4) gratings mounted onto more durable backgrounds. The success of the new cards was evaluated by testing 3- and 12-month-old human infants and comparing the results to those obtained with the prototype cards.

Results indicate that the new CS cards were very successful. Compared to the prototype, which required 10 to 15 minutes, the new card procedure was completed by most subjects within 5 to 8 minutes. Also, compared to the prototype, individual contrast sensitivity functions (CSFs) of 12-month-olds tested with the new cards are more typical of healthy infants as measured by more rigorous behavioral procedures. Surprisingly, however, group CSFs obtained with the new cards were lower than those obtained with the prototype, a discrepancy that may be due to differences in space average luminance between the two sets of cards. In all, the new CS card procedure possesses several merits which give it potential as a technique for widespread adoption by both researchers and clinicians.

Acknowledgements

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Modification of the Infant Contrast Sensitivity Card Procedure

The assessment of spatial vision throughout life is essential for the maintenance of healthy eyesight. Spatial vision, arguably the most important visual function, refers to the ability to detect objects and patterns in the environment. More specifically, it involves a number of essential visual tasks such as the detection of brightness changes, edges, borders, and contours within a visual scene (Schwartz, 1999). The precision of spatial vision is most often measured with tests of visual acuity (i.e., the smallest object that can be recognized or resolved). Despite the importance of spatial vision, a large number of people of all ages suffer from impairment in this visual function. Recent data suggest that, worldwide, between 38 and 50 million people are legally blind (i.e., corrected visual acuity worse than 20/200). Moreover, it is estimated that an additional 110 million people possess low spatial vision (i.e., corrected visual acuity better than 20/200, but worse than 20/60; Grimes, Scardino, & Martone, 1992; Thylefors, Négrel, Pararajasegaram, & Dadzie, 1995). In Canada, The Canadian National Institute for the Blind (1997) services over 90 000 visually impaired people.

Importantly, studies investigating underlying factors show that many types of spatial vision loss are often preventable, especially among young children and the elderly (Grimes et al., 1992; Jackson & Glasson, 1998). A simple but essential component of prevention is the routine assessment of early spatial vision. In infants and young children, measurement of spatial vision is particularly critical, as it may lead to the detection of the visual anomalies which cause unnecessary deprivation of normal visual experience.

Numerous studies of mammals (including humans) have shown that even brief periods of early visual deprivation may permanently impair spatial vision and visual development.

Effects of Visual Deprivation During Infancy

Several studies of kittens and primates have investigated the effects of early visual deprivation. In these experiments, one or both eye(s) in the developing animal are sutured shut to provide a type of visual deprivation similar to that which occurs naturally in human infants with eye disease. Collectively, the animal experiments indicate that early monocular deprivation leads to structural abnormalities in the visual system, such as smaller than normal cell bodies in both the lateral geniculate nucleus (LGN) and the visual cortex, and also substantial decrements in functional spatial vision (Hubel & Wiesel, 1970; Mitchell, Murphy, & Kaye, 1984; von Noorden, Dowling, & Ferguson, 1970; Wiesel & Hubel, 1965). For example, Mitchell et al. (1984) demonstrated that as little as 4 weeks of monocular visual deprivation in newborn kittens reduced visual acuity by 70% as compared to the nonsutured eye.

Similar results have been found in studies of human infants and children who have suffered from early visual deprivation due to one of three visual anomalies, namely; (1) strabismus, a condition in which one eye is turned inward (i.e., esotropia) or outward (i.e., exotropia) relative to the other; (2) anisometropia, unequal refractive error in the two eyes; (3) congenital cataracts, large opacities on the lens or cornea which scatter light as it enters the eye, and thus, prevent the formation of a sharp visual image on the retina. In all cases, visual input to the central nervous system is seriously degraded. If these conditions remain untreated, the region of the visual cortex responsible for the weak or defective eye will suppress information from that eye. More significantly, untreated visual anomalies lead to lower regional cerebral blood flow in the extrastriate visual cortex, and marked reductions in spatial vision in the absence of obvious optical or retinal abnormalities (Abrahamsson & Sjöstrand, 1988; Birch, Stager, & Wright,1986; Cheng, Hiles, Biglan, & Pettapiece, 1991; Drummond, Scott, & Keech, 1989; Imammura, Richter, Fischer, Lennerstrand, Franzen, Rydberg, Andersson, Schneider, Onoe, Watanabe, & Langstrom, 1997; Jacobson, Mohindra, & Held, 1981; Lloyd, Dowler, Kriss, Speedwell, Thompson, Russell-Eggitt, & Taylor, 1995; Maurer & Lewis, 1993; Maurer, Lewis, & Brent, 1989; Maurer, Lewis, Brent, & Levin, 1999; Odom, Hoyt, & Marg, 1981; Rogers, Bremer, & Leguire, 1987; Wali, Leguire, Rogers, & Bremer, 1991). For example, Jacobson et al. (1981) found that beginning at birth, just 11.5 weeks of human monocular deprivation could reduce visual acuity by over 90% (from 20/150 to less than 20/1600) when compared to the nondeprived eye.

In all, the above studies indicate that humans and other mammals undergo a critical period during which it is essential that the visual system is exposed to normal visual experience. For humans, the consensus is this critical period lasts from about the 4th to the 36th postnatal month (Billson, Fitzgerald, & Provis, 1985; Cheng et al., 1991). If visual anomalies are detected before, or during this period, recovery of spatial vision may be substantial (Birch et al., 1986; Cheng et al., 1991; Drummond et al., 1989; Lloyd et al., 1995; Maurer & Lewis, 1993; Maurer et al., 1989; Maurer et al., 1999; Wali et al., 1991).

It is important to note, however, that treatment may be effective if begun as late as 7 years of age, but recovery is much more modest in comparison to early intervention (Leguire, Rogers, & Bremer, 1990). For instance, Drummond et al. (1989) demonstrated that subjects who began treatment for congenital visual anomalies before 18 months of age, and remained compliant throughout, achieved an average visual acuity of 20/40 in the affected eye. Despite the significance of the early detection of visual insults during routine pediatric eye examinations, this is often problematic as many conditions tend to be quite subtle (such as anisometropia, slight strabismus, a “lazy eye”, or a small cataract). Therefore, it is essential that in addition to the structural examination of the infant's eyes, functional spatial vision be thoroughly assessed in order to detect any visual anomalies, and thus maximize recovery. This is especially important for infants at risk for early vision problems, including preterm infants, or those with identified genetic or neurological disorders such as cerebral palsy or Down syndrome (Courage, Adams, Reyno, & Kwa, 1994; Orel-Bixler, Haegerstrom-Portnoy, & Hall, 1989).

Traditional Assessment of Spatial Vision

Typically, spatial vision has been assessed with tests of visual acuity. Visual acuity is defined as the limit of maximal spatial resolution, and is generally measured by estimating the smallest visual target that can be correctly identified. The Snellen ("Big E") test is most often used to measure visual acuity in literate, verbal subjects. The subject stands a fixed distance (most often 20 feet) from a Snellen chart that contains rows of letters which become progressively smaller as one reads from top to bottom.

Beginning at the top, the subject reports the letters one row at a time until he/she can no longer correctly identify them. The last row of letters correctly identified provides an estimate of visual acuity. In a normal adult, Snellen visual acuity is 20/20 (or 6/6 in metric units).[1]

Obviously, an alternative method must be used to measure visual acuity in infants who are neither verbal nor literate. An alternative approach for estimating visual acuity has been to use square wave grating stimuli instead of the numbers, letters, or other recognizable objects that are used with recognition acuity methods (see McDonald, Dobson, Sebris, Baitch, Varner, & Teller, 1985). Gratings consist of repeating black and white stripes of a specific thickness or *spatial frequency*. Spatial frequency is a measure of the size of the elements in a pattern (in this case, the width of the stripes), and is defined as the number of cycles of the elements (i.e., one black stripe and one white stripe) that repeat within 1 degree of visual space (c/deg). Thus, gratings of low spatial frequency (e.g., 1 c/deg) consist of relatively thick stripes, and gratings of high spatial

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[1] Snellen visual acuity is expressed in relation to the test distance (normally 20 feet, or 6 meters) and in comparison to a person with normal sight (Sekuler & Blake, 1994). If one is able to identify at a distance of 20 feet, the letters that a person with normal sight can identify at the same distance, he/she possesses a visual acuity of 20/20. However, visual acuity can be better or worse than 20/20. For example, a visual acuity of 20/60 implies that one can identify at a distance of 20 feet, the letters that a person with normal sight can identify at 60 feet. Conversely, a visual acuity of 20/15 means that one can identify at 20 feet, the letters that a person with normal sight can identify at 15 feet. Note, test distance is not varied during the Snellen Test. Instead, the denominator in the Snellen visual acuity fraction represents letter size which is correlated to test distance.

frequency (e.g., 10 c/deg) consist of much thinner stripes. A grating with a spatial frequency of 30 c/deg corresponds to an approximate Snellen fraction of 20/20.

Traditionally, two methods have been used to measure grating acuity in nonverbal subjects. First, researchers have used electrophysiological techniques such as the recording of visually evoked potentials (VEP). Electrodes are attached to the scalp of the infant to measure the electrical activity in the visual cortex, and the subject is then presented with a series of gratings. If a particular grating produces a measurable VEP, it is assumed that the infant's visual system can detect it. Thus, an infant's visual acuity is assessed by presenting a number of gratings, and the grating with the highest spatial frequency that yields a recordable response, provides an estimate of threshold. A second method for measuring grating acuity is to use a behavioral, psychophysical technique. One example is the forced-choice preferential looking method (FPL). FPL is based upon the pioneering work of Fantz (1965), who found that infants prefer to fixate a patterned over an unpatterned stimulus. In a typical FPL experiment, the subject is presented with two stimuli; a pattern (in this case, a grating), and an unpatterned stimulus of equal average luminance (a "blank"). If the infant demonstrates a consistent visual preference for the patterned stimulus by fixating on it more than the unpatterned stimulus (as determined by a trained observer), it is assumed that he/she can detect the elements in the pattern. The grating with the highest spatial frequency for which an infant demonstrates a reliable preference (e.g., 65-75% of the time), is taken as an estimate of his/her visual acuity.

Although visual acuity tests provide an important general index of spatial vision, they alone are not sufficient to provide an accurate estimate of the visual system's ability to detect all of the patterns in the everyday visual world (Banks & Dannemiller, 1987). Whereas visual acuity tests measure sensitivity to objects that vary in size, they do so with targets (i.e., letters, gratings, etc.) which are at fixed, high *contrast* levels (usually 85-95%). Contrast refers to the difference in light intensity between an object and its surroundings (contrast is defined as $C = [I_{max} - I_{min}]/[I_{max} + I_{min}]$ where I_{max} and I_{min} refer to the brightest and darkest portions of the target, respectively). However, real world objects also vary in contrast across a broad range, from very high to very low levels (Banks & Dannemiller, 1987; Mäntyjärvi, Autere, Silvennoinen, & Myöhänen, 1989). Consequently, it is not surprising that humans with certain visual or neural anomalies (e.g., macular degeneration, cerebral lesions, etc.) may perform within the normal range on visual acuity tests, yet complain of blurred vision when viewing objects at lower contrast or illumination levels (Adams, Mercer, Courage, & van Hof-van Duin, 1992; Banks & Dannemiller, 1987; Bodis-Wollner, 1972; Lennerstrand & Ahlström, 1989). Thus, because of the variation in contrast levels in the real world, visual acuity testing has limited diagnostic value for the complete evaluation of spatial vision.

Assessment of Contrast Sensitivity

The inadequacies of visual acuity tests highlight the need for a more comprehensive index of spatial vision. Such an index is the measurement of *contrast sensitivity* (CS) which assesses sensitivity to targets that vary *both* in spatial frequency and in contrast. Specifically, this method estimates the minimum amount of contrast (i.e., the contrast threshold) required to detect sine wave gratings at different spatial frequencies. The reciprocal of each threshold can then be plotted to form a contrast sensitivity function (CSF). The typical mean CSF of a group of human adults is shown in Figure 1. The function resembles an inverted U with maximum CS (i.e., lowest contrast threshold) at intermediate spatial frequencies (about 3-5 c/deg), and reduced CS at progressively lower and higher spatial frequencies.

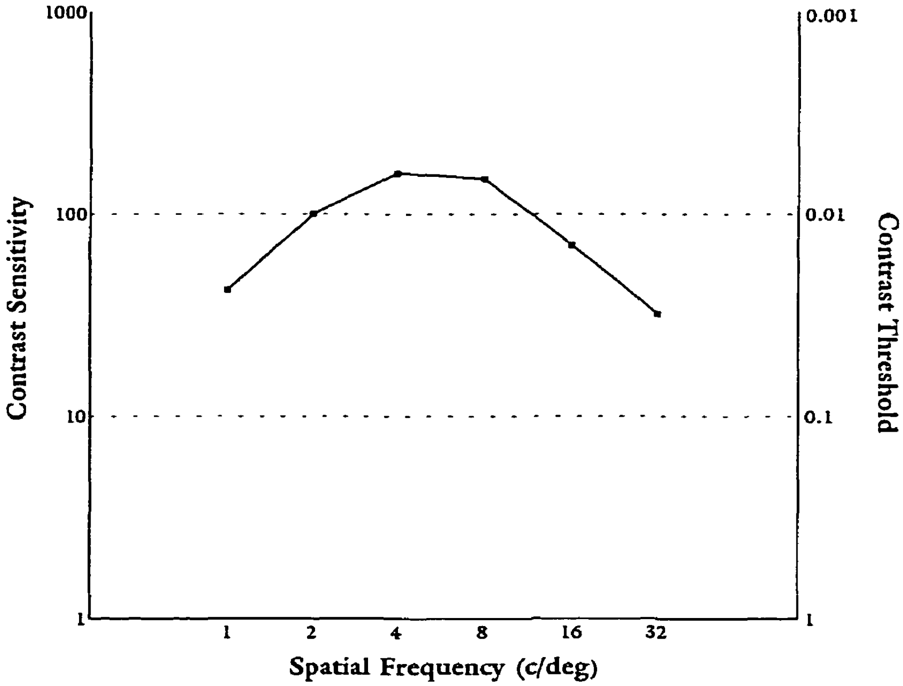

Figure 1. Typical adult CSF (data are drawn from Ginsburg, Evans, Cannon, Owsley, & Mulvanny, 1984). Note, contrast sensitivity units are the reciprocal of contrast threshold.

The measurement of CS provides researchers and clinicians with several advantages over more traditional indices of spatial vision functioning (such as the measurement of visual acuity). First, because the theoretical basis for CS measurement is derived from a combination of Fourier's theorem and linear systems analysis, the CSF provides a more powerful measure of vision as it can predict a subject's sensitivity to patterns of all sizes and contrasts (Banks & Dannemiller, 1987; Banks & Salapatek, 1981; Mohn & van Hof-van Duin, 1991; Sekuler & Blake, 1994). Specifically, Fourier's theorem posits that *any* two-dimensional image can be reduced to a combination of sine wave gratings, each of which is represented by a set of equations which specify spatial frequency, contrast, orientation, and phase of the image's component sine waves.[2] Thus, Fourier analysis of any visual stimulus provides a complete description of its elemental input to the visual system. The role of the CSF is that it represents the visual system's sensitivity, and within the context of linear systems analysis, it acts as the primary linear filter mechanism through which the elemental input passes. Therefore, the CSF provides a description of whether the pattern will be perceived (for more elaboration, see footnote below).

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[2] In essence, the human visual system itself acts as a Fourier analyzer as it breaks any two-dimensional image down into its Fourier components (i.e., spatial frequency, contrast, orientation, and phase; Aslin, 1987). Once this is accomplished, the components are filtered by the CSF and then reassembled to produce a final perceptual representation of the image (Schwartz, 1999). Only those combinations of spatial frequencies and contrasts to which one is sensitive (i.e., those which lie below one's CSF and are thus, above threshold) are included in the final representation. Therefore, if one's CSF is known, his/her perceptual representation of any two-dimensional image can be determined.

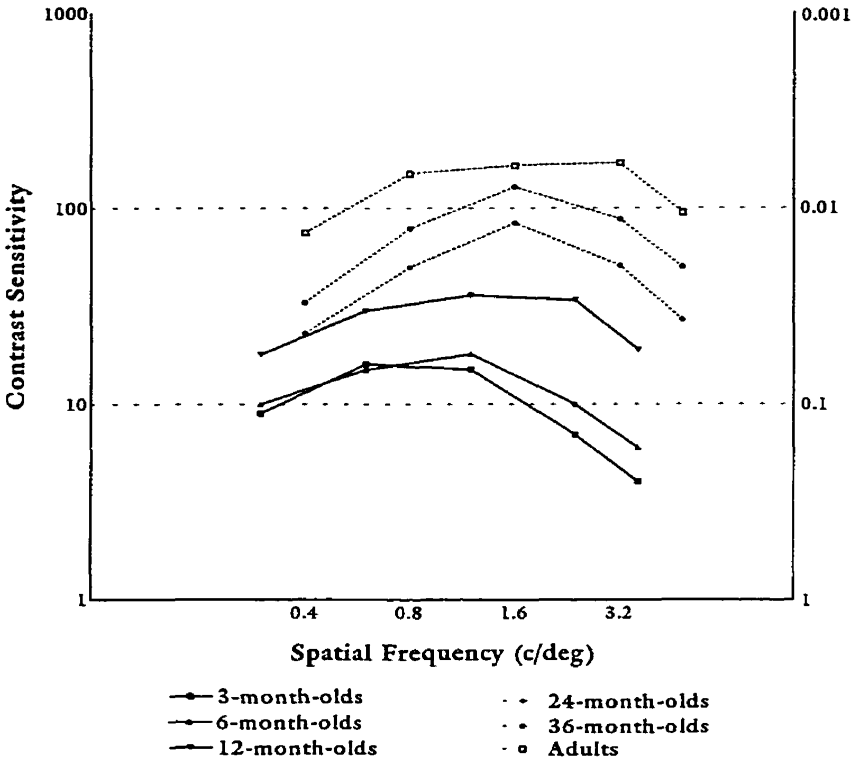

Figure 2. Mean contrast sensitivity functions of 3-, 6-, 12-, 24-, 36-month-olds, and adults (data are drawn from Adams & Courage, 1993; Courage, Piercey, & Adams, 1997).

Another advantage of CS assessment is that it allows researchers to follow the early development of spatial vision. A representational data set containing the CSFs of 3-, 6-, 12-, 24-, 36-month-old, and adult subjects is shown in Figure 2. Although, the CSFs of all six age groups display the typical inverted-U shape, the children's CSFs are lower and are shifted to the left when compared to adults. This implies that infant spatial vision is limited to lower spatial frequencies and to higher contrast levels (Adams et al., 1992; Banks & Dannemiller, 1987; Beazely, Illingworth, Jahn, & Greer, 1980; Pirchio, Spinelli, Fiorentini, & Maffei, 1978). As Figure 2 shows, however, the CSF shifts upward and rightward with development. Although estimates vary, adultlike levels appear to be attained between 7 years of age and early adolescence (Beazely et al., 1980; Ellemberg, Lewis, Liu, & Maurer, 1999; Scharre, Cotter, Stein-Block, & Kelly, 1990).

Another feature of the CSF is that it contains components which correspond to specific aspects of spatial vision. For instance, using a least squares method, one can extrapolate the intersection between the high spatial frequency portion of the function and the abscissa (see Banks & Salapatek, 1981). This provides an estimate of the smallest pattern that can be resolved at maximal (100%) contrast, i.e., one's visual acuity. Whereas behavioral studies of CS estimate that typical adult visual acuity is between 30-50 c/deg, infant visual acuity is much lower, measuring approximately 3, 4, 6, and 9 c/deg for 1, 3, 6, and 12-months-olds, respectively (Adams & Courage, 1996; Adams et al., 1992; Banks & Dannemiller, 1987; Banks & Salapatek, 1978; Banks & Salapatek, 1981; Hainline & Abramov, 1997; Mohn & van Hof-van Duin, 1991). These estimates are useful to vision researchers as they are in agreement with FPL studies of grating acuity (Gwiazda, Brill, Mohindra, & Held, 1980; Mayer & Dobson, 1982; Riddell, Ladenheim, Mast, Catalino, Nobile, & Hainline, 1997). VEP studies of infant CS yield estimates of visual acuity that tend to be higher, perhaps due to either the limited infant attention required in comparison to FPL studies, or to the conservative threshold criterion implemented in most FPL studies (Mohn & van Hof-van Duin, 1991). Specifically, acuity is about 5 c/deg at 1 and 3 months, but rises very rapidly to 12-18 c/deg at 6 months of age (Hamer, Norcia, & Tyler, 1989; Harris, Atkinson, & Braddick, 1976; Norcia & Tyler, 1985; Norcia, Tyler, & Hamer, 1988; Norcia, Tyler, Hamer, 1990; Pirchio, et al., 1978; Sokol, 1978).

A second component of the CSF is its peak. The specific location of the peak reveals two important aspects of spatial vision. First, as an index of maximum contrast sensitivity, it represents the minimum amount of contrast that one is capable of seeing. Behavioral data reveal that in adults, the peak typically falls between 120 and 220 CS units (i.e., between 0.83% and 0.45% contrast) though it may be as high as 350 CS units (0.29% contrast) under some conditions (Arundale, 1978; Corwin & Richman, 1986; Derefeldt, Lennerstrand, & Lundh, 1979; Ginsburg et al., 1984; Gwiazda, Bauer, Thorn, & Held, 1997; Hainline & Abramov, 1997; Mäntyjärvi et al., 1989; Scharre et al., 1990; Scialfa, Tyrell, Garvey, Deering, Leibowitz, & Goebel, 1988). Behavioral studies of infant and toddler CS reveal peaks at 8, 30, 70, and 100 CS units for 1-, 12-, 24-, and 36-month-olds, respectively (Adams & Courage, 1996; Adams et al., 1992; Atkinson, Braddick, & Moar, 1977; Banks & Salapatek, 1978; Hainline & Abramov, 1997). Electrophysiological data appear to show the same developmental trends, except that peak CS tends to be higher, with some subjects reaching adult levels as early as 2-3 months of age (Norcia, Tyler, & Allen, 1986; Norcia et al., 1988; Norcia et al., 1990; Pirchio et al., 1978). The second significant aspect of the peak is the spatial frequency at which it occurs (i.e., the spatial frequency that corresponds to the lowest contrast threshold). Banks and Salapatek (1981) argue that the spatial frequency representing peak CS corresponds to the average receptive field size of the subject's retinal ganglion cells. Specifically, a peak at low spatial frequencies indicates large receptive field sizes, whereas a peak at higher spatial frequencies indicates small receptive field sizes. Behavioral estimates of the location of peak CS reveal that it is below 1 c/deg until about 6 months of age, but then rises rapidly, possibly reaching adult levels (i.e., 3-5 c/deg) as early as 3 to 5 years of age (Adams & Courage, 1996; Adams et al., 1992; Atkinson, French, & Braddick, 1981; Banks & Salapatek, 1978; Beazely et al., 1980; Bradley & Freeman, 1982; Gwiazda et al., 1997; Hainline & Abramov, 1997; Richman & Lyons, 1994; Scharre et al., 1990). The few VEP estimates of peak spatial frequency show that it develops rapidly from 0.25 c/deg at 1 month, to about 1-2 c/deg at 3 months, and reaches adult levels by about 6 months of age (Harris et al., 1976; Norcia et al., 1990; Pirchio et al., 1978).

A third component of the CSF is the progressively reduced sensitivity to contrast at lower spatial frequencies. This component of the CSF is referred to as *low frequency attenuation* (Banks & Salapatek, 1981). The consensus among researchers is that low frequency attenuation is due to the influence of lateral inhibition within the visual system (Adams & Courage, 1993; Adams et al., 1992; Atkinson, Braddick, & Braddick, 1974; Atkinson et al., 1977; Banks & Dannemiller, 1987; Banks & Salapatek, 1976; Banks & Salapatek, 1978; Banks & Salapatek, 1981; Mohn & van Hof-van Duin, 1991). Lateral inhibition is an index of the antagonistic neural interaction between adjacent cells or cell groups throughout the different levels of the visual system (Sekuler & Blake, 1994).

Functionally, lateral inhibition filters out extraneous information in order to emphasize sharp intensity changes. Most behavioral studies agree that lateral inhibition appears between 1 and 2 months of age (Adams et al., 1992; Atkinson et. al., 1977; Banks & Salapatek, 1978; but see, Gwiazda et al., 1997; Hainline & Abramov, 1997). On the other hand, electrophysiological studies do not show any agreement as to onset, with several studies failing to show evidence of substantial lateral inhibition, even in older infants (Atkinson, Braddick, & French, 1979; Norcia et al., 1986; Norcia, et al., 1988; Norcia, et al., 1990).

A final advantage of CS measurement is its practical and clinical potential. As mentioned above, visual and neural anomalies may exist but may not be detected by Snellen tests or by other traditional techniques of visual assessment. However, the measurement of CS may detect anomalies and provide important information regarding their effect on functional vision. For example, it has been demonstrated that the CSF provides a more complete description of the visual losses suffered by subjects with amblyopia, cataracts, Parkinson's disease, and cerebral lesions (Bodis-Wollner, 1972; Bodis-Wollner, Marx, Mitra, Bobak, Mylin, & Yahr, 1987; Bulens, Meerwaldt, van der Wildt, & Keemink, 1986; Bulens, Meerwaldt, van der Wildt, & van Deursen, 1987; Chylack, Padhye, Khu, Wehner, Wolfe, McCarthy, Rosner, & Friend, 1993; Hess & Holliday, 1992; Levi & Klein, 1992; Loeffler, Wise, & Gans, 1990; Rogers et al., 1987; Sjöstrand, 1981).

Although the use of the VEP and FPL techniques has been successful for measuring CS in infants, both have problems that limit their clinical/practical application. The major advantage of the VEP technique is that it requires little infant attention (Atkinson et al., 1974; Haegerstrom-Portnoy, 1993; Mohn & van Hof-van Duin, 1991). However, VEP equipment is very expensive, sophisticated, and the attachment of electrodes to the infant's scalp may distress the subject and his/her parents (Adams & Courage, 1993). Another criticism is that the results of VEP studies seldom agree on the development of the critical CSF components described above. This is likely to be as a result of the wide variability in measurement parameters across VEP studies, for instance, the temporal frequency or the luminance of the stimuli (Mohn & van Hof-van Duin, 1991).

Behavioral procedures such as FPL, on the other hand, are inexpensive, unsophisticated, and likely provide a more representative measure of an infant's functional vision (Riddell et al., 1997). However, these procedures suffer from other shortcomings as they rely on the use of psychophysical staircase procedures in which numerous trials (e.g., 20 or more) are required to make an estimate of a single contrast threshold. Also, FPL techniques restrict observers to only one behavioral cue (fixation direction), and thus, multiple trials are needed for each contrast level (Adams et al., 1992). Therefore, although estimates obtained using FPL are likely to be accurate, the procedure is time-consuming and often leads to low completion rates (Atkinson et al., 1977; Atkinson et al., 1981; Banks & Salapatek, 1978; Bradley & Freeman, 1982; Gwiazda et al., 1997; Peterzell, Werner, & Kaplan, 1993; Scharre et al., 1990).

Furthermore, FPL procedures typically apply a conservative threshold criterion in which the observer must correctly determine the location of the gratings on at least 65-75% of the trials (Atkinson et al., 1977; Atkinson et al., 1981; Banks & Salapatek, 1978; Gwiazda et al., 1997; Mohn & van Hof-van Duin, 1991; Scharre et al., 1990). Such a criterion may lead to an underestimate of an infant's true visual abilities (Mohn & van Hof-van Duin, 1991).

The Contrast Sensitivity Card Procedure

In response to the limitations of the above techniques, Adams et al. (1992) have developed a prototype CS card procedure modeled after the well-established Teller Acuity Cards that were designed for measuring visual acuity (McDonald et al., 1985). The Teller Acuity Cards are a series of 15 rectangular cards, each measuring 56 x 25.5 cm. Each card contains a high contrast, vertical, square wave grating (12.5 by 12.5 cm) located 7.5 cm to the left or right of a central peephole. The spatial frequency of the gratings range from 0.22 to 27 c/deg (when viewed at 38 cm) and the space average luminance of the gratings matches the background of the cards. The cards are presented following a modified FPL procedure. The test begins with the presentation of a card containing a grating one of the lowest spatial frequencies. Testing continues with cards containing gratings of progressively higher spatial frequencies, until it is judged by a trained observer that the subject can not detect the grating. The subject's visual acuity is estimated as the finest grating detected. Compared to traditional FPL techniques, the Teller Acuity Card procedure reduces test completion time as it allows the observer to use several behavioral cues simultaneously (e.g., pointing, head movements, strength of response, etc.) in order to decide if the subject can detect a grating.

Similarly, the CS card test developed by Adams et al. (1992) consists of 40 rectangular, matteboard cards, each measuring 50 by 28 cm. Each card contains two circular stimuli (radius = 3.8 cm); a test grating and a "control" stimulus which are mounted to the left and right of a central 3 mm peephole. The stimuli are cut out from the Vistech (VCTS) 6500 chart, a wall chart used to measure CS in adults. The test grating contains a computer-generated, vertical, sine wave grating, whereas the control stimulus appears as a blank circle of equal average luminance. The cards are divided into five sets, based on the spatial frequency of the grating (0.3, 0.6, 1.2, 2.4, or 3.6 c/deg when viewed from 60 cm), and within each set, the gratings range in contrast from about 33% to 0.3%. In a similar fashion to the use of the Teller Acuity Cards, each subject is assessed with a modified, rapid FPL procedure (see McDonald et al., 1985). To test each spatial frequency set, the card containing the grating with the highest contrast is presented first. Testing of the set then proceeds with cards containing gratings of lower contrast. The grating of the lowest contrast detected by the subject is taken as an estimate of the contrast threshold.

The CS card procedure provides researchers with several significant advantages over traditional psychophysical techniques. First, and perhaps most importantly, contrast sensitivity estimates can usually be obtained from infants in one 10-15 minute session as compared to a traditional FPL procedure, which may require up to five separate 20 minute sessions (Adams & Courage, 1993; Adams et al., 1992; Atkinson et al., 1977). Also, the cards are relatively inexpensive, portable, and easy to use. However, there are drawbacks to the procedure. Infants sometimes become fussy and uninterested, and are unable to continue. For example, Adams et al. (1992) tested 1-, 3-, 6-, and 12-month-olds and reported completion rates of 74%, 87%, 100%, and 80%, respectively. Also, observers were not always completely confident in decision-making, especially when testing with gratings that were near contrast threshold levels. Therefore, in its present form, it is unlikely that this technique can be easily adapted for clinical settings. Adams et al. (1992) note that these findings may be due to the relatively small size of the stimuli (the diameter is only 7.2° when viewed from 60 cm). Thus, the gratings may not be particularly salient for younger infants who possess limited visual fields (see Courage & Adams, 1990; Lewis & Maurer, 1992; Mohn & van Hof-van Duin, 1986; Sireteanu, Fronius, & Constantinescu, 1994) nor for older infants and children who are easily distracted.

A second criticism of the CS cards is that the gratings contain a limited number of cycles due to their relatively small size. It has been demonstrated that the contrast threshold for a particular spatial frequency is constant with stimuli containing 7 or more cycles, but decreases progressively with progressively fewer cycles (Hoekstra, van der Goot, van den Brink, & Bilsen, 1974; Kelly, 1975). As the lower spatial frequency gratings of the prototype CS cards contain between 2.5 and 4 cycles, the method may underestimate CS at these spatial frequencies.

Another drawback of the CS cards is the selection of the gratings' contrast values. First, as the highest contrast grating in each set is only 20% to 33%, young infants are often unable to detect them, and therefore, contrast thresholds cannot be obtained for some spatial frequencies. Second, the average contrast step size (i.e., the difference in contrast levels between adjacent gratings within each spatial frequency set) is quite large, measuring 24.7 CS units, or 0.24 log CS units. Thus, the CS cards can only crudely estimate a subject's contrast threshold, and may not detect subtle visual anomalies (Scialfa et al., 1988). In order to obtain more precise contrast threshold estimates, a finer contrast step size must be used. A final criticism of the CS cards concerns their lack of durability. The cards are constructed with 1.5 mm thick matteboard. Although this material is quite light and portable, it is not durable. Therefore, the cards are easily damaged, particularly at the edges. Before the CS cards can gain widespread clinical acceptance, it is important that they be able to withstand the rigors of everyday use and storage.

Although the CS cards are arguably the best option to thoroughly measure spatial vision in nonverbal subjects, they are in need of improvement. Therefore, the purpose of the present research was to develop a *new* set of CS cards in response to the above criticisms. The development of the new cards was a painstaking process which required nearly a year of pilot work (*see Appendix A*). Specifically, custom software and precise printing techniques were used to construct a set of CS cards with several important modifications. First, the new cards contain circular gratings which subtend a visual angle of 16.3° at a distance of 60 cm, and have an area over 5 times larger than the prototype gratings. Gratings of this size should maintain the interest of the subjects throughout testing, and thereby reduce completion time, increase completion rate, and boost observer confidence in decision-making. Furthermore, given their large size, all gratings contain at least 7 cycles in order to prevent the underestimation of CS at low spatial frequencies. Second, the contrast levels of the cards have been customized to measure CS in infants and toddlers from birth to 2 years of age. Each spatial frequency set contains a high contrast "warm-up" card (40% to 55% contrast) which should be detected by even the youngest subjects. Third, the average contrast step size has been reduced from 24.7 CS units to 6.4 CS units (i.e., from 0.24 to 0.16 log CS units). Smaller contrast step sizes should allow more precise estimation of contrast thresholds at all spatial frequencies. Fourth, the background of the new CS cards are constructed with millboard (hardcover book stock) instead of matteboard. Millboard should provide greater durability without substantially increasing weight.

In the present study, the effectiveness of the modified version of the CS cards is evaluated by testing groups of 4- and 12-month-old infants and comparing these data to those obtained from groups tested with the prototype. If the new cards are successful, they may represent a substantial contribution to the assessment of spatial vision in infants as researchers and clinicians could potentially obtain a more thorough, precise estimate of an infant's spatial vision in just a fraction of the time required by other procedures.

Method

Subjects

The subjects were two groups of 20 infants (26 male, 14 female), selected from two different ages: 4 months (mean age = 3.7 months; range = 3.4 - 4.2 months) and 12 months (mean age = 12.0 months; range = 11.7 - 12.4 months). Subjects were recruited shortly after birth by research assistants who personally visited parents at the Grace Hospital in St. John's, NF. At birth, all subjects were healthy, weighed at least 2500 grams, and were at least 37 weeks gestation. Since then, all infants had to have been free of any detectable ophthalmic and neural diseases. Four additional 12-month-old infants were tested but excluded from the final sample, three because they did not complete testing, and one because of an experimenter error (failure to record some of the data).

Stimuli and Apparatus

Testing was conducted with a new set of CS cards developed by the author, Dr. Russell J. Adams, and Avery E. Earle (all of the psychology department at Memorial University; see Appendix A). The new cards were based on the prototype (Adams et al., 1992) and modeled closely after the Teller Acuity Cards (see McDonald et al., 1985). However, the newer version of the cards contains a number of important modifications (discussed in the introduction above). A comparison of a new vs. a prototype card is shown in Figure 3 below.

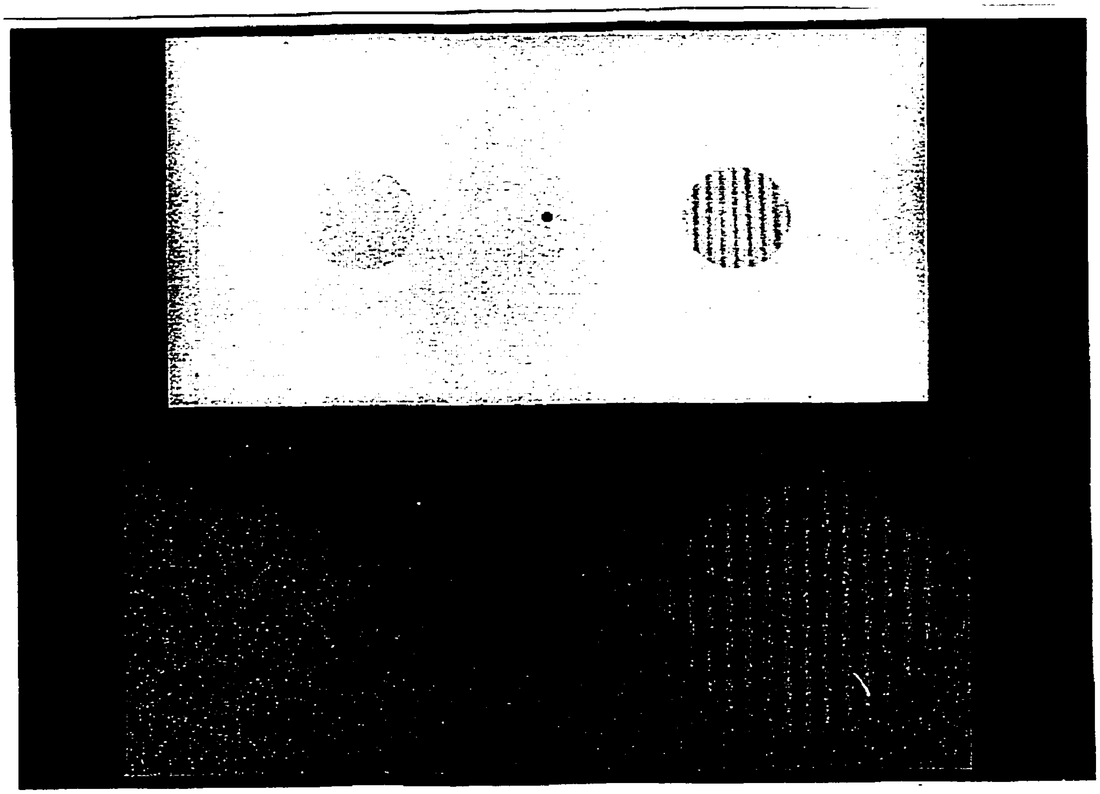

Figure 3. Photograph of a prototype CS card (top) and a new CS card (bottom). Each card contains a grating with approximately the same spatial frequency and contrast.

The new version of the CS cards consists of forty 56 by 28 cm rectangular cards. Each card contains two large circles located 8 cm to the left and right of a central 2 mm peephole. The circles have a diameter of 17.5 cm and subtend a diameter of 16.3° at a viewing distance of 60 cm. One circle is the *test* grating, which consists of a vertical, sine wave grating of a given spatial frequency and contrast. The other circle, the *control* grating, is a vertical, sine wave grating with the same spatial frequency, but with a contrast of 0% (i.e., all stripes are of equal luminance). Thus, the control stimulus appears as a blank/subliminal field with luminance equal to the average luminance of the test grating and the background of the card, and to adults, is indiscriminable from the background of the card. A subthreshold grating was used as a control stimulus (vs. leaving one side of the card blank) in order to ensure that the infants could not detect the test grating by relying on an edge/grating artifact (e.g., a slight brightness difference existing on the outer edges of the grating). Therefore, if an artifact existed, it would be present on both sides of the peephole and would not reveal the location of the test grating.

All gratings were generated by composing suitable programs in Postscript[3] programming language, and then printing onto resin coated (RC) paper with a Linotronic Mark 40 EX image setter, adjusted to 2540 dots per inch with the default halftone mask (Adobe Systems Incorporated, 1986; 1990). RC paper is slightly stronger and glossier than regular paper, and portrays a sharper, more accurate printed image. The paper was then heat pressed onto 2 mm thick millboard. Under testing conditions, the average luminance of each grating and the background of the card was 35 cd/m^2 as measured with a cal-SPOT 400VF photometer (The Cooke Corporation, London, Ontario).

The new CS cards are divided into five sets (of eight) based on the spatial frequency of the test gratings in each set (0.4, 0.8, 1.6, 3.2, or 6.4 c/deg). The spatial frequency, CS value, and contrast of each card are listed in Table 1. The table also shows that each spatial frequency set includes a high contrast (40 - 55%) warm-up card which is presented to capture the attention of the infant at the onset of testing with the set. The

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[3] Postscript is a registered trademark of Adobe Systems Incorporated.

warm-up cards representing each spatial frequency set are shown in Figure 4.

Table 1. Approximate contrast sensitivity values (CS units) of test gratings in each spatial frequency set (new CS cards). Contrast percentages are shown in brackets. Note, the CS value of each test grating is simply the reciprocal of its contrast.

Spatial Frequency	Card Number							
Set	1	2	3	4	5	6	7	8
A. 0.4 c/deg	1.8 (55.0)	4.4 (22.9)	6.2 (16.2)	8.7 (11.5)	12.3 (8.1)	17.5 (5.7)	24.4 (4.1)	38.5 (2.6)
B. 0.8 c/deg	2.5 (40.0)	7.2 (13.9)	10.2 (9.8)	14.3 (7.0)	20.4 (4.9)	28.6 (3.5)	40.0 (2.5)	62.5 (1.6)
C. 1.6 c/deg	2.5 (40.0)	8.2 (12.2)	11.5 (8.7)	16.4 (6.1)	23.3 (4.3)	32.3 (3.1)	45.5 (2.2)	71.4 (1.4)
D. 3.2 c/deg	1.8 (55.0)	4.6 (21.7)	6.5 (15.3)	9.2 (10.9)	13.0 (7.7)	18.5 (5.4)	25.6 (3.9)	41.7 (2.4)
E. 6.4 c/deg	1.8 (55.0)	2.1 (47.0)	3.0 (33.3)	4.3 (23.6)	6.0 (16.7)	8.5 (11.8)	11.9 (8.4)	18.9 (5.3)

To reduce distraction, the cards were presented from behind a three panel grey matteboard backboard that matched, approximately, the average luminance of the cards (see Figure 5). The backboard consists of two 120 x 30 cm side panels attached by hinges to a 120 x 71 cm center panel which allow for easy storage and portability. The center panel contains a 52 x 22 cm opening through which the cards are presented.

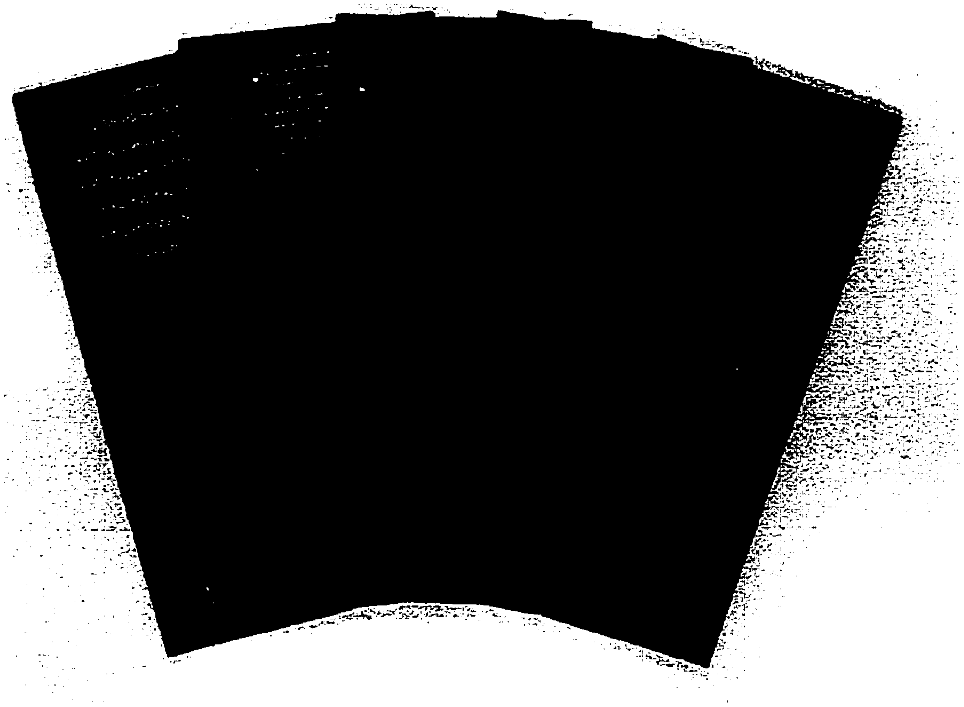

Figure 4. Photograph of the high contrast "warm-up" card representing each spatial frequency set. Note, due to the limitations of the scanning procedure, the grating for spatial frequency set E (i.e., last card on the right) cannot be seen in the picture. However, the grating is clearly visible to adults at the testing distance of 60 cm.

Procedure

Upon arrival at the testing room, the procedure was explained to the parent and several examples of the CS cards were shown. The parent was given a consent form explaining that inclusion in the study was voluntary, that the child or parent could discontinue the study at any time, and that the child and his/her data would remain anonymous (see Appendix B). The study protocol was approved by the Memorial

University of Newfoundland Faculty of Science Ethics Review Board.

Figure 5. Photograph of a 3-month-old infant during testing with the warm-up card from spatial frequency set A.

All testing was conducted binocularly with the procedure modeled very closely on that used for the prototype (Adams et al., 1992). The infant was seated on the parent's lap 60 cm away from the opening in the center panel of the screen. First, the warm-up card from one of the sets was presented to allow the experimenter to gain a familiarity with the particular head movements and fixation patterns that the child demonstrates when presented with a grating that should be easily detected. Also, the card was often rotated 180° on the vertical plane so as to position the test grating on the opposite side of the peephole. The experimenter then determined whether the infant's movement and fixation switched to the opposite side of the card. It is important to note that at this point, the location of the grating was known to the experimenter. Following the presentation of the warm-up card, a blank was shown which contains two subthreshold stimuli. This provided the experimenter with an opportunity to see how the subject would react to a grating that could not be detected.

After becoming familiar with the visual behavior of the infant, the testing phase began. To initiate the test, the experimenter (who was also the observer) presented the highest contrast card from one of the five sets of spatial frequencies (see Figure 5). This card was presented repeatedly and often rotated (as described above) until the experimenter could conclude either the infant showed a consistent preference for one particular side of the card (presumably the side containing the grating), or he/she displayed no particular preference for either side of the card (i.e., the infant could not detect the grating). Note, the experimenter was never permitted to look at the front of the card until *after* the decision was made, and thus, did not know the location of the test grating during the presentation of the card. Typically, at least 3 to 4 presentations were required before the observer could decide whether a grating could be detected. Decisions could be based on numerous cues including the speed, direction, and duration of the infant's fixation and/or head movement. If it was concluded that the subject showed a preference for one side of the card, the experimenter turned the card over to verify that this side did indeed contain the test patch. If the decision was correct, the card with the next lowest contrast test grating in that set was presented. However, if the previous card appeared to be detected rather easily by the infant, the experimenter could skip a contrast level or two in the set, and thus, minimize the number of cards and time required to complete the test. This procedure was then continued with the remaining cards of lower contrast until it was judged that the infant showed no preference for either side of a card. The lowest contrast grating detected by the subject was taken as a measure of the contrast threshold for that spatial frequency. After the infant's threshold was determined for a set representing a particular spatial frequency, the experimenter presented the highest contrast card from another spatial frequency set. This procedure continued with all remaining sets, and the set order was counterbalanced across subjects.

To ensure accuracy throughout testing, it is important that the experimenter avoids making hasty decisions as there is a 0.5 probability that the experimenter can correctly determine the location of the test grating by chance (i.e., a "lucky hit"). Although it is impossible to determine when this occurs, one *can* determine its counterpart (a false alarm). This occurs when the experimenter judges that the infant shows a preference for the side of the card that does not contain the grating. In the present study, a conservative procedure was used to deal with false alarms, so as not to overestimate the CS of the infant. If a false alarm occurred, the same card was presented on two consecutive trials. If the experimenter correctly determined the location of the grating each time, it was concluded that the grating was detected. However, if on at least one of these presentations, it was judged that the infant showed no such preference, then it was decided that the grating was not detected. If three false alarms occurred with one infant, the data were considered inconsistent, testing was stopped, and these data were not included in further analysis. In the present study, less than 5% (28/620) of all decisions resulted in a false alarm, and in all cases, these false alarms were resolved using the procedure described above.

Results

To analyze the results of the new test, the data from subjects in the present study were compared to those obtained from infants of similar ages (3- and 12-months-old) who were tested previously with the prototype version of the cards (Adams et al., 1992). Specifically, the two versions of the test were compared on two measures of efficiency (completion rate and completion time), the similarity of the CS estimates, and the typicality of the individual CSFs. It is important to note that data of 4-month-olds in the present study were compared to those of 3 month-olds from the prototype study. Ideally, 3-month-olds would have been tested in the present study, but a variety of factors made this age group difficult to recruit. However, the groups were still quite similar as the age difference between them was approximately 3 weeks (13.1 vs. 16.3 weeks). Therefore, for convenience, the infants in the present study will be referred to as 3-month-olds.

Completion Rates

With the new cards, 100% (20/20) of the 3-month-olds and 87% (20/23) of the 12-month-olds completed testing. All three 12-month-olds, who did not complete the test, became uncooperative during the early stages. Although completion rates were slightly lower for the prototype cards (87% for the 3-month-olds; 80% for the 12-month-olds), this difference between card type was not significant at either age (all $\mathbf{p} > 0.05$), likely because completion rates were very high for both versions.

Completion Time

Time necessary to complete testing was measured for all subjects. However, it is important to note that completion time is in part determined by the number of cards required by the subject. Therefore, it is possible that low completion times may not reflect the efficiency of the cards, but rather the presentation of relatively few cards during a test. Thus, a subject with low CS may be presented with fewer cards, and record lower completion times than a subject with high CS. Also, a test with a smaller contrast step size (i.e., the new test) may take longer to complete as potentially more cards are presented in order to obtain a threshold estimate at each spatial frequency. Therefore, the time required to present a single card (i.e., time per card) was also measured for each subject. Mean completion time per test and time per card for each age group (3-month-olds vs. 12-month-olds) and card type (new vs. prototype) are presented in Table 2 below. The table reveals two important findings: (1) Completion time was lower with the new cards than with the prototype (Grand mean = 6.5 min. vs. 9.5 min.) and (2) time per card was lower with the new cards than with the prototype (Grand mean = 25.6 sec. vs. 34.7 sec.). Independent t-tests confirmed that the new cards resulted in lower completion times for both 3-month-olds ($t = 3.436$, $df = 38$, $\mathbf{p} < 0.005$) and 12-month-olds ($t = 3.595$, $df = 34$, $\mathbf{p} < 0.005$). Also, at both ages, the new cards required less time per card than did the prototype (3-month-olds: $t = 2.714$, $df = 38$, $p < 0.05$; 12-month-olds: $t = 3.089$, $df = 34$, $p < 0.005$).

Table 2. Mean completion time and time per card for each age group and card type. Standard deviations are shown in brackets.

Age Group	Completion Time (min.)		Time per Card (sec.)	
	New Cards	Prototype	New Cards	Prototype
3-month-olds	5.1 (1.1)	6.4 (1.2)*	22.9 (6.9)	28.1 (5.3)*
12-month-olds	7.9 (2.7)	13.4 (6.2)*	28.3 (10.7)	42.9 (17.6)*
Grand Mean	6.5 (2.5)	9.5 (5.4)*	25.6 (9.3)	34.7 (14.2)*

*$p < 0.05$

A final set of analyses was conducted to compare completion time and time per card between 3- and 12-month-olds tested with the new cards. An independent t-test revealed that 3-month-olds had significantly faster completion times than 12-months-olds ($t = 4.27$, $df = 38$, $p < 0.001$). However, this difference was likely to be a result of the presentation of fewer cards to 3-month-olds (mean = 13.7 cards) vs. 12-month-olds (mean = 17.3 cards); this suggestion was supported by the finding that there was no significant difference in time per card between the two age groups ($t = 1.91$, $df = 38$, $p >$

0.05).

Estimates of Contrast Sensitivity: New Cards vs. Prototype

Statistical comparisons between CS estimates obtained with the new cards and the prototype cards were difficult as gratings in the two versions of the test differ slightly in spatial frequency. Specifically, the new cards measured CS at 0.4, 0.8, 1.6, 3.2, and 6.4 c/deg, whereas the prototype cards measured CS at 0.3, 0.6, 1.2, 2.4, and 3.6 c/deg. To remedy this problem, the CSF of each individual in the prototype study was re-plotted and CS was then estimated at the spatial frequency values used in the new study (0.4, 0.8, 1.6, and 3.2 c/deg) by interpolating the relevant points with Graphpad: Prism 3 software[4] (Graphpad Software Incorporated, 1999). CS at 6.4 c/deg was not used in statistical analyses for two reasons: First, contrast threshold estimates were not obtained at this spatial frequency for 85% of the 3-month-olds and 10% of the 12-month-olds tested with the new cards. Second, contrast thresholds could not, with any accuracy, be estimated to 6.4 c/deg for infants tested with the prototype cards because this spatial frequency was too far beyond the highest spatial frequency (3.6 c/deg) used in that study. The mean CSF for each age group and card type are shown in Figure 6. All CSFs display the typical inverted U-shape with peak CS at an intermediate spatial frequency and reduced CS at progressively lower and higher spatial frequencies. As expected, the CSF develops substantially from 3 to 12 months of age as it shifts upward and rightward. For data from

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[4] Graphpad: Prism 3 is a registered trademark of Graphpad Software Incorporated.

the present study (i.e., data obtained with the new cards), a 2 (age) x 4 (spatial frequency) analysis of variance (ANOVA) revealed that the CS for 12-month-olds was significantly higher than that for 3-month-olds [F(1,38) = 77.20, **p** < 0.001] and analyses of simple effects indicated that this difference was significant across all spatial frequencies (all **p** < 0.05). The ANOVA also revealed a significant age x spatial frequency interaction [F(3,114) = 5.57, **p** < 0.05)]. However, as the curves for 3- and 12-month-old infants are roughly parallel, this interaction is probably accounted for by a shift in peak CS from about 0.8 c/deg at 3 months of age, to about 1.6 c/deg at 12 months of age.

Figure 6 also reveals a second, somewhat unexpected result. The group CSFs were higher for subjects tested with the prototype cards than for those tested with the new cards. This finding is surprising as it suggests higher CS estimates are obtained with the prototype cards (which are more difficult to use and require more time and effort). The effect of card type on CS was analyzed by conducting a 2 (card type) x 4 (spatial frequency) mixed ANOVA for each age group. The analysis revealed that CS scores were significantly higher for subjects tested with the prototype cards than for those tested with new cards [3-month-olds: F (1, 38) = 15.16, **p** < 0.001; 12-month-olds: F(1, 38) = 9.50, **p** < 0.05]. Again, analyses of simple effects indicated that this difference was significant across all spatial frequencies for 12-month-olds (all **p** < 0.05), and across all spatial frequencies except 3.2 c/deg for 3-month-olds (all **p** < 0.05). In each case, there was no significant interaction between card type and spatial frequency [3-month-olds: F(3, 114) = 2.08, **p** > 0.05; 12-month-olds: F(3, 114) = 0.51, **p** > 0.05]. Prototype CSFs are higher, but the functions for each card type possess the same basic shape.

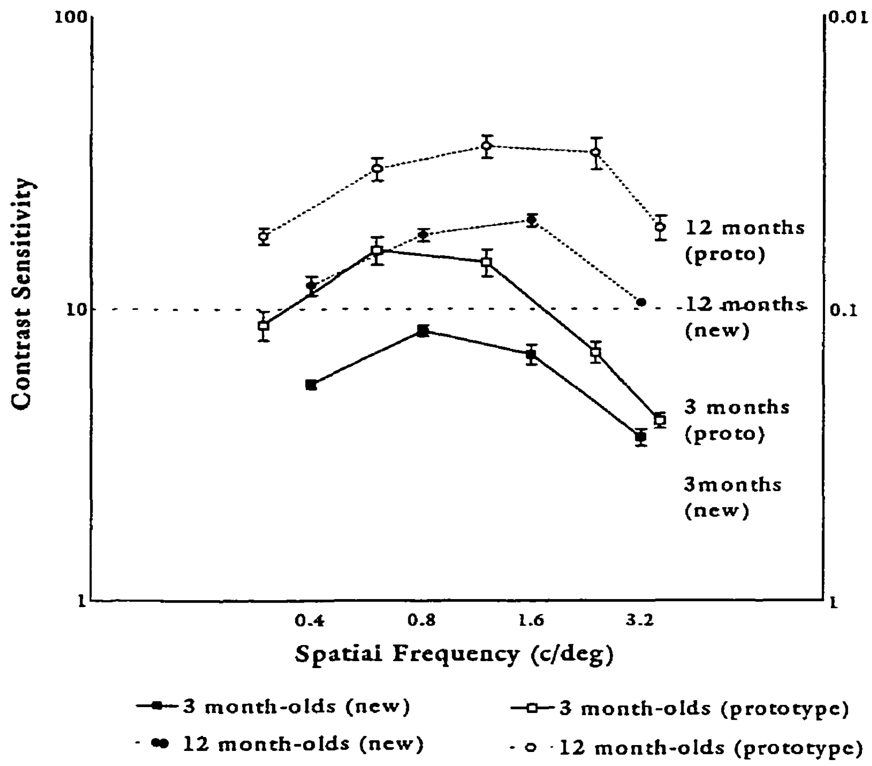

Figure 6. Mean CSFs of 3- and 12-month-olds tested with the new or prototype CS cards. Vertical bars represent standard errors. When not shown, standard error bars are smaller than the size of the data points.

Typicality of Individual CSFs: New Cards vs. Prototype

A final point of interest was to determine which version of the CS cards provides a higher percentage of typical individual CSFs. To determine this, individual CSFs were plotted for all subjects and each was judged as typical or atypical. A CSF was considered typical only if it displayed an overall, characteristic inverted U-shape, with peak CS at an intermediate spatial frequency, and reduced CS at progressively lower and higher spatial frequencies (Adams et al., 1992). An infant's CSF was considered atypical if it possessed one or both of the following; (1) an overall "linear shape" (i.e., the function consists of horizontal or diagonal line as opposed to an inverted U) or (2) a "notch" loss (i.e., a sharp decrease in CS that is isolated at a single, intermediate spatial frequency) in which the CSF increased at an angle of at least 20° above the horizontal plane immediately before and after the loss (Note: 20° was chosen as this represents a rather substantial notch in a CSF). Thus, atypical curves tend to be abnormally shaped and much more difficult to interpret. To illustrate, Figure 7 shows examples of typical CSFs (Figure 7a), a linear CSF (Figure 7b), and a "notch" loss (Figure 7b). Following the above criterion, two independent raters, each blind to card type and subject characteristics, rated the typicality of each CSF. 75% (15/20) of the 3-month-olds and 85% (17/20) of the 12-month-olds tested with the new cards possessed typical CSFs. With the prototype cards, 65% (13/20) of the 3-month-olds and 60% (12/20) of the 12-month-olds exhibited typical CSFs. The observers agreed on 95% (76/80) of all decisions. Although the new cards provided a higher proportion of typical CSFs for both age groups, normal approximations to the binomial indicated that this difference was significant only for 12-month-olds (3-month-olds: $Z = 0.94$, $\mathbf{p} > 0.05$; 12-month-olds: $Z = 3.14$, $\mathbf{p} < 0.05$).

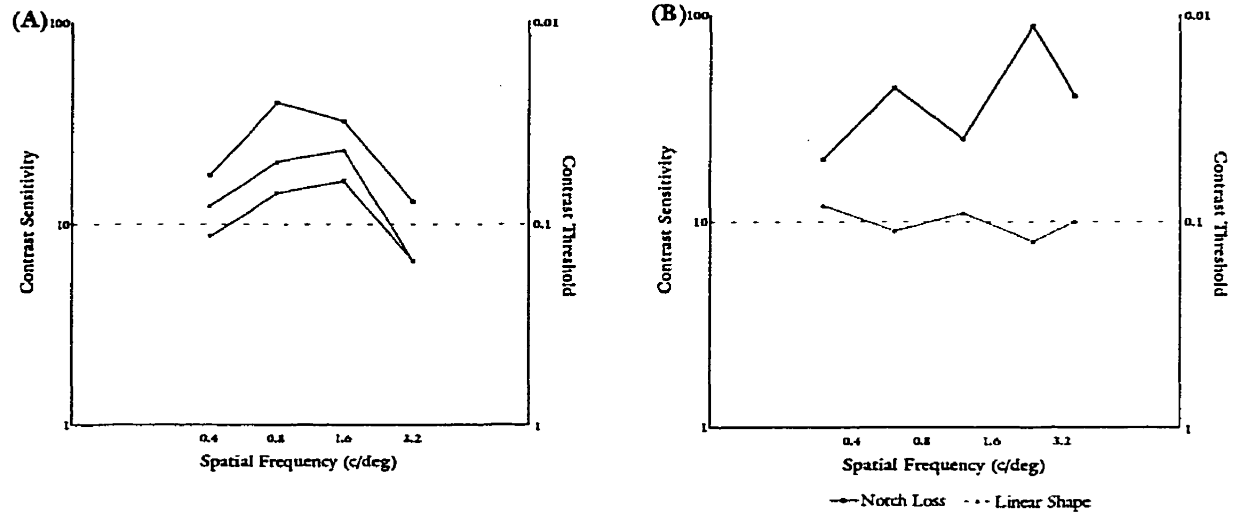

Figure 7. (A) Examples of typical individual CSFs obtained for 12-month-old subjects. (B) Examples of atypical individual CSFs obtained for 12-month-old subjects. The top CSF shows a distinct notch loss at 1.2 c/deg (i.e., the third data point from the left), whereas the lower CSF shows an overall "linear shape".

Discussion

Success of the New Procedure

The new CS card procedure evaluated in this thesis represents a significant technological advance in the assessment of spatial vision in human infants. The design of the new cards was an ambitious project which involved considerable pre-experimental effort (see Appendix A). First, custom software needed to be developed which could create gratings of *any* contrast level, spatial frequency, and size. The most challenging task, however, was to develop and maintain perfect printing conditions in order to produce cards of consistent luminance and precise contrast. Results indicate the new CS cards are highly successful and that they possess two significant advantages over the prototype. First, the new cards are very efficient. On average, contrast thresholds can be measured at four or five spatial frequencies in only 5-8 minutes, compared to the prototype and other FPL techniques which require between 10 and 100 minutes (Adams et al., 1992; Atkinson et al., 1977; Atkinson et al., 1981; Banks & Salapatek, 1978; Bradley & Freeman, 1982; Gwiazda et al., 1997). This efficiency is likely to be due to the size of the gratings, which maintain the attention of the infant throughout the test, and elicit quick responses that are obvious to the observer.

A second advantage of the new cards is that they incorporate a small contrast step size which allows for more precise estimation of contrast threshold. As a result, compared to those tested with the prototype, 12-month-olds tested with the new cards were more likely to display the typical, interpretable CSFs of healthy infants. Thus, the new cards are likely more accurate, at least when testing 12-month-olds. This is important from a clinical standpoint, as it reduces the likelihood of a misdiagnosis, and/or the necessity to repeat the test several times in order to obtain reliable estimates, a problem noted in a study with the previous version of the cards (Adams, Courage, & Drover, 2000). Also, though it may be argued that the small contrast step size may limit the clinical utility of the new CS cards (i.e., for obtaining measurements from infants and toddlers with extremely low CS), additional cards with gratings of very high contrast (60% to 80%) could be added in the future to assess such subjects.

Although the new CS cards improve upon the efficiency and accuracy of the prototype, the problem of missing data points persists to some degree. Despite the inclusion of a high contrast warm-up card at each spatial frequency, contrast thresholds could not be obtained at the highest spatial frequency (6.4 c/deg) for most of the youngest subjects (i.e., 3-month-olds). However, missing data points did not appear to pose a serious problem in the present study as the four lowest spatial frequencies were sufficient to generate interpretable CSFs for almost all subjects.

Comparison to Other FPL Techniques

In general, the above results suggest that the new CS card procedure was highly successful for measuring CS in preverbal infants. Yet, an evaluation of the procedure is not complete without comparing the CS data of the present study to those from other studies employing more rigorous, but time-consuming psychophysical techniques. This comparison reveals several important findings. First, the shapes of the group CSFs in the present study are consistent with other FPL studies (Adams & Courage, 1993; Adams et al., 1992; Atkinson et al., 1977; Banks & Salapatek, 1978; Gwiazda et al., 1997; Peterzell et al., 1993). Second, the pattern of CS development from 3 to 12 months of age agrees with previous studies (Adams et al., 1992; Atkinson et al., 1977; Banks & Salapatek, 1978; Gwiazda et al., 1997; Peterzell et al., 1993). Specifically, the CSF shifted upward and rightward to include lower contrasts and higher spatial frequencies. Third, as in previous studies, the spatial frequency corresponding to peak CS increased from about 0.8 c/deg to about 1.6 c/deg (Atkinson et al., 1977; Banks & Salapatek, 1978; Gwiazda et al., 1997).

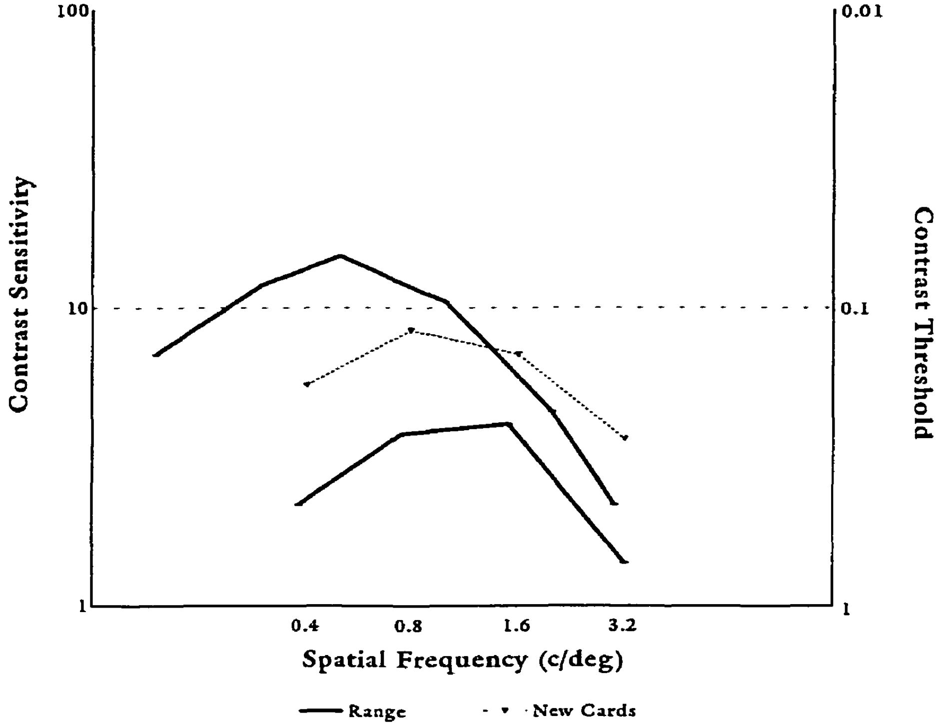

Figure 8. The range of contrast threshold estimates (solid lines) obtained from 3- to 4-month-olds tested previously with other FPL procedures (data are drawn from Atkinson et al.,1977; Banks & Salapatek, 1978; Gwiazda et al., 1997; Peterzell et al., 1993). The CSFs of 3-month-olds from the present study (dashed line) are included for comparison.

However, one aspect of the CSFs of the present study is not completely consistent with other studies. Figure 8 shows the range of CS estimates obtained from 3- to 4-month-olds tested previously with FPL procedures, plotted as composite CSFs representing the upper and lower limits of these data (Atkinson et al., 1977; Banks & Salapetek, 1978; Gwiazda et al., 1997; Peterzell et al., 1993). The dashed line in Figure 8 shows the CSF of the 3-month-olds tested in the present study. The Figure reveals that at the lowest spatial frequencies (0.4 and 0.8 c/deg), estimates of the present study fall well within the range of those obtained from previous studies, but at 1.6 and 3.2 c/deg, threshold estimates are slightly above that range. The reason for these relatively elevated thresholds at higher spatial frequencies is not clear, yet it must be kept in mind that the range of CS data is based only on a limited number of FPL studies. Note, a similar comparison of maximum/minimum threshold estimates could not be conducted for the data of 12-month-olds as only one other data set exists for infants at this age (Adams et al., 1992).

Comparison to the Prototype

Although Figure 8 suggests that the contrast threshold estimates for the 3-month-olds are relatively high compared to other FPL studies, they are in fact, lower than those for the prototype study (see Figure 6 reprinted below from the results section). Furthermore, this discrepancy in CS estimates between the new and prototype CS cards also exists for the data of the 12-month-olds. There are at least two explanations for these differences. First, the discrepancy between the new and prototype CS cards may be due to observer differences. However, this is unlikely as the experimenter of the present study also used the prototype cards to measure CS for many of the infants in a previous experiment (Adams et al., 2000), and obtained results consistent with those shown below (Adams et al., 1992).

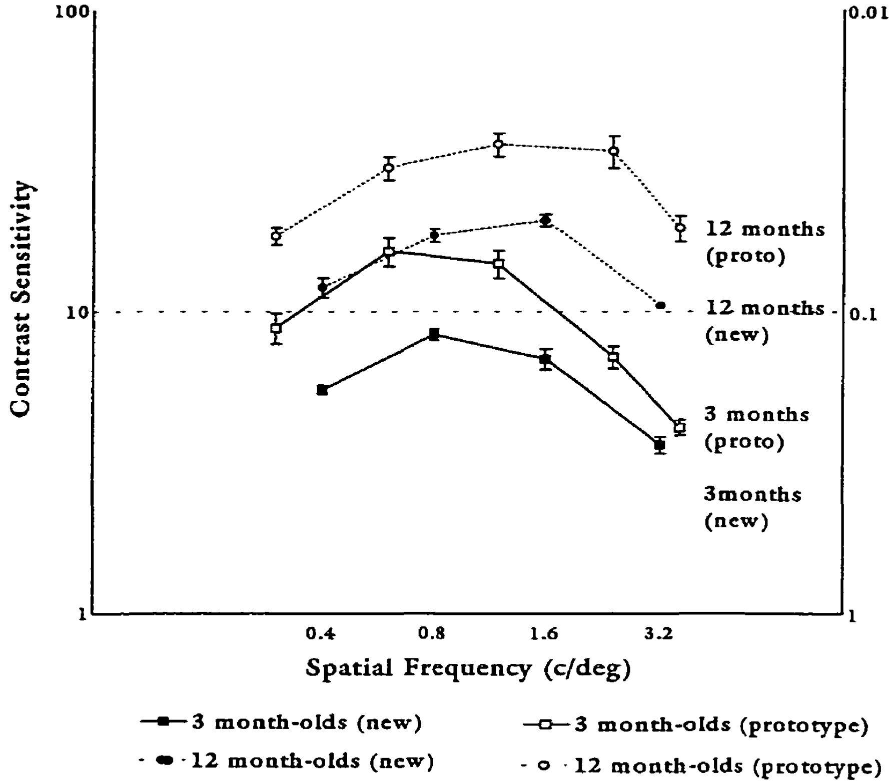

Figure 6 (reprinted from the results section). Mean CSFs of 3- and 12-month-olds tested with the new or prototype CS cards. Vertical bars represent standard errors. When not shown, standard error bars are smaller than the size of the data points.

A second reason for the disparity in the CS estimates is the physical differences between the new and protoype CS cards. For example, under testing conditions, the space average luminance of the gratings (and background) of the new CS cards is 35 cd/m^2, 0.31 log cd/m^2 lower than that for the prototype (70 cd/m^2). Studies with adults demonstrate that within the low to mid photopic range (the range of the present study), both CS and visual acuity improve with corresponding increases in stimulus and background luminance levels (Banks, Geisler, & Bennet, 1987; Haegerstrom-Portnoy, Brabyn, Schneck, & Jamposky, 1997; Rovamo, Mustonen, & Näsänen, 1994; Sheedy, Bailey, & Raasch, 1984; Sturr, Kline, & Taub, 1990; Waugh & Levi, 1993). This increase in CS appears to be due to greater efficiency of photon capture by photoreceptors at progressively higher luminance levels (Waugh & Levi, 1993). Moreover, the effects of stimulus luminance level on spatial vision appear to be greater at low contrast levels, a result which implies that stimulus luminance may play a large role at near-threshold contrast levels (Haegerstrom-Portnoy et al., 1997).

The effect of luminance on the spatial vision of infants is less well understood as the infant visual system is relatively immature in comparison to that of the adult. For example, infants and children display shorter outer cone segments and less dense foveal cone packing in comparison to adults (Banks & Bennett, 1988; Ellemberg et al., 1999). As a result of these immaturities, it is likely that infants are affected differently by increases in stimulus and background luminance. Only two FPL studies to date have measured spatial vision at several photopic luminance levels (Brown, Dobson, & Maier, 1987; Dobson, Salem, & Carson, 1983). Each investigated the effects of luminance on visual acuity only. Results of these studies indicate that visual acuity is relatively independent of stimulus and background luminance levels. However, it is important to note that the data of Brown et al. (1987) indicate a sharp loss of visual acuity of 2-month-olds at an average stimulus luminance of approximately 32 cd/m^2. Coincidentally, this level is virtually identical to the average luminance of the gratings used in the present study, and may account for the relative decrease in CS as compared to the prototype.

No single experiment has measured infant CS at several photopic luminance levels. However, a comparison of FPL studies which estimate CS at a single stimulus luminance level demonstrates a consistent finding: Those conducted at lower luminance levels report lower peak CS than those conducted at higher luminance levels. For instance, using the prototype cards as a reference (Adams & Courage,1993; Adams et al., 1992), FPL studies that employed lower average stimulus luminance showed that for each log unit (cd/m^2) decrease in luminance there is an average decrease of 1.1 log CS units in peak CS (Atkinson et al., 1977; Banks & Salapatek, 1978; Beazley et al., 1980; Gwiazda et al., 1997; Peterzell et al., 1993). Based on these estimates, one would predict that peak CS obtained with the new cards should be 0.34 log CS units lower than that obtained with the prototype cards. A calculation of the mean log difference in peak CS between the new and protoype cards reveals that for the new cards, peak CS was 0.28 log units lower for 3-month-olds and 0.25 log CS units lower for 12-month-olds. These values correspond very closely to that which was predicted. Although this finding suggests that luminance may have been a factor in the relatively low CS found in the present experiment, future studies measuring infant CS at several photopic luminance levels must be conducted to confirm this suggestion.

Conclusions

In conclusion, the modification of the CS card procedure was very successful. The new CS cards represent a substantial improvement over the prototype in terms of both the typicality of individual CSFs and the efficiency of the procedure: As a result, a much better estimate of CS can now be obtained in most infants in only 5 to 8 minutes.

This is of particular importance to clinicians who must often conduct *two* monocular assessments of spatial vision. Moreover, the new cards possess the same strengths of the prototype in that they are inexpensive, portable, and easy to use. Given these assets, the new CS card procedure is arguably the best option for infant CS measurement for both researchers and clinicians. This bodes well for its wide-spread adoption as a technique for the early measurement of this most vital aspect of human vision.

References

Abrahamsson, M. & Sjöstrand, J. (1988). Contrast sensitivity and acuity relationship in strabismic and anisometropic amblyopia. British Journal of Ophthalmology, 72, 44-49.

Adams, R. J. & Courage, M. L. (1993). Contrast sensitivity in 24- and 36-month-olds as assessed with the contrast sensitivity card procedure. Optometry and Vision Science, 70, 97-101.

Adams, R. J. & Courage, M. L. (1996). Monocular contrast sensitivity in 3- to 36-month-old human infants. Optometry and Vision Science, 73, 546-551.

Adams, R. J., Courage, M. L., & Drover, J. R. (2000). Retest variability of human contrast sensitivity: How many tests are sufficient? Optometry and Vision Science, 77, 90-95.

Adams, R. J., Mercer, M. E., Courage, M. L., & van Hof-van Duin, J. (1992). A new technique to measure contrast sensitivity in human infants. Optometry and Vision Science, 69, 440-446.

Adobe Systems Incorporated (1986). Postscript language tutorial and cookbook. Adobe Systems Incorporated: Author.

Adobe Systems Incorporated (1990). Postscript language reference manual/Adobe systems (2nd Edition). Adobe Systems Incorporated: Author.

Arundale, K. (1978). An investigation into the variation of human contrast sensitivity with age and ocular pathology. British Journal of Ophthalmology, 62, 213-215.

Aslin, R. N. (1987). Visual and auditory development in infancy. In J. D. Osofsky (Ed.), Handbook of Infant Development (2nd ed. pp. 5-98). New York: John Wiley and Sons Inc.

Atkinson, J,. Braddick, O., & Braddick, F. (1974). Acuity and contrast sensitivity of infant vision. Nature, 247, 403-404.

Atkinson, J., Braddick, O., & French, J. (1979). Contrast sensitivity of the human neonate measured by the visual evoked potential. Investigative Ophthalmology Visual Science, 18, 210-213.

Atkinson, J., Braddick, O., & Moar, K. (1977). Development of contrast sensitivity over the first 3 months of life in the human infant. Vision Research, 17, 1037-1044.

Atkinson, J., French, J., & Braddick, O. (1981). Contrast sensitivity function of preschool children. British Journal of Ophthalmology, 65, 525-529.

Banks, M. S. & Bennett, P. J. (1988). Optical and photoreceptor immaturities limit the spatial and chromatic vision in human neonates. Journal of the Optical Society of America, 5, 2059-2079.

Banks, M. S. & Dannemiller, J. L. (1987). Infant visual psychophysics. In P. Salapatek & L. Cohen (Eds.). Handbook of Infant Perception (pp. 115-177). New York: Academic Press.

Banks, M. S., Geisler, W. S., & Bennett, P. J. (1987). The physical limits of grating visibility. Vision Research, 27, 1915-1924.

Banks, M. S. & Salapatek, P. (1976). Contrast sensitivity function of the infant visual system. Vision Research, 16, 867-869.

Banks, M. S. & Salapatek, P. (1978). Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. Investigative Ophthalmology and Visual Science, 17, 361-365.

Banks, M. S. & Salapatek, P. (1981). Infant pattern vision: A new approach based on the contrast sensitivity function. Journal of Experimental Psychology, 31, 1-45.

Beazley, L. D., Illingworth, D. J., Jahn, A., & Greer, D. V. (1980). Contrast sensitivity in children and adults. British Journal of Ophthalmology, 64, 863-866.

Billson, F. A., Fitzgerald, B. A., & Provis, J. M. (1985). Visual deprivation in infancy and childhood: Clinical aspects. Australian and New Zealand Journal of Ophthalmology, 13, 279-286.

Birch, E. E., Stager, D. R., & Wright, W. W. (1986). Grating acuity development after early surgery for congenital cataracts. Archives of Ophthalmology, 104, 1783-1787.

Bodis-Wollner, I. (1972). Visual acuity and contrast sensitivity in patients with cerebral lesions. Science, 178, 769-771.

Bodis-Wollner, I., Marx, M. S., Mitra, S., Bobak, P., Mylin, L., & Yahr, M. (1987). Visual dysfunction in Parkinson's disease. Brain, 110, 1675-1698.

Bradley, A. & Freeman, R. D. (1982). Contrast sensitivity in children. Vision Research, 22, 953-959.

Brown, A. M., Dobson, V., & Maier, J. (1987). Visual acuity of human infants at scotopic, mesopic and photopic luminances. Vision Research, 27, 1845-1858.

Bulens, C., Meerwaldt, J. D., van der Wildt, G. J., & Keemink, C. J. (1986). Contrast sensitivity in Parkinson's disease. Neurology, 36, 1121-1125.

Bulens, C., Meerwaldt, J. D., van der Wildt, G. J., & van Deursen, J. B. P. (1987). Effect of levodopa treatment on contrast sensitivity in Parkinson's disease. Annals of Neurology, 22, 365-369.

The Canadian National Institute for the Blind (1998). CNIB Client Statistics 1997 [Brochure]. Canadian Ophthalmological Society: Author.

Cheng, K. P., Hiles, D. A., Biglan, A. W., & Pettapiece, M. C. (1991). Visual results after early surgical treatment for unilateral congenital cataracts. Ophthalmology, 98, 903-910.

Chylack, L. T. Jr., Padhye, N., Khu, P. M., Wehner, C., Wolfe, J., McCarthy, D., Rosner, B., & Friend, J. (1993). Loss of contrast sensitivity in diabetic patients with LOCS II classified cataracts. British Journal of Ophthalmology, 77, 7-11.

Corwin, T. R. & Richman, J. E. (1986). Three clinical tests of the spatial contrast sensitivity function: A comparison. American Journal of Optometry and Physiological Optics, 63, 413-418.

Courage, M. L. & Adams, R. J. (1990). The early development of visual acuity in the binocular and monocular peripheral fields. Infant Behavior and Development, 13, 123-128.

Courage, M. L., Adams, R. J., Reyno, S., & Kwa, P. G. (1994). Visual acuity in infants and children with Down syndrome. Developmental Medicine and Child Neurology, 36, 586-593.

Courage, M. L., Piercey, G., & Adams, R. J. (1997). Development of contrast sensitivity from birth to 9 years. Investigative Ophthalmology and Visual Science, 38, S62.

Derefeldt, G., Lennerstrand, G., & Lundh, B. (1979). Age variations in normal human contrast sensitivity. Acta Ophthalmologica, 57, 679-690.

Dobson, V., Salem, D., & Carson, J. B. (1983). Visual acuity in infants-the effect of variations in stimulus luminance within the photopic range. Investigative Ophthalmology and Visual Science, 24, 519-522.

Drummond, G. T., Scott, W. E., & Keech, R. (1989). Management of monocular congenital cataracts. Archives of Ophthalmology, 107, 45-51.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. Vision Research, 39, 2325-2333.

Fantz, R. L. (1965). Visual perception from birth as shown by pattern selectivity. Annals of the New York Academy of Sciences, 118, 793-814.

Ginsburg, A. P., Evans, D. W., Cannon, M. W. Jr., Owsley, C., & Mulvanny, P. (1984). Large-sample norms for contrast sensitivity. American Journal of Ophthalmology and Physiological Optics, 61, 80-84.

Graphpad Software Incorporated (1999). Graphpad Prism: User's Guide. Graphpad Software Incorporated: Author.

Grimes, M. R., Scardino, M. A., & Martone, J. F. (1992). Worldwide blindness. Nursing Clinics of North America, 27, 807-816.

Gwiazda, J., Bauer, J., Thorn, F., & Held, R. (1997). Development of spatial contrast sensitivity from infancy to adulthood: Psychophysical data. Optometry and Vision Science, 74, 785-789.

Gwiazda, J., Brill, S., Mohindra, I., & Held, D. (1980). Preferential looking acuity in infants from two to fifty-eight weeks of age. American Journal of Optometry and Physiological Optics, 57, 428-432.

Haegerstrom-Portnoy, G. (1993). New procedures for evaluating vision function of special populations. Optometry and Vision Science, 70, 306-314.

Haegerstrom-Portnoy, G., Brabyn, J., Schneck, M. E., & Jampolsky, A. (1997). The SKILL card: An acuity test of reduced luminance and contrast. Investigative Ophthalmology and Visual Science, 38, 207-216.

Hainline, L. & Abramov, I. (1997). Eye movement-based measures of development of spatial contrast sensitivity in infants. Optometry and Vision Science, 74, 790-799.

Hamer, R. D., Norcia, A. M., & Tyler, C. W. (1989). The development of monocular and binocular VEP acuity. Vision Research, 29, 397-408.

Harris, L., Atkinson, J., & Braddick, O. (1976). Visual contrast sensitivity of a 6-month-old infant measured by the evoked potential. Nature, 264, 570-571.

Hess, R. F. & Holliday, I. E. (1992). The spatial localization deficit in amblyopia. Vision Research, 32, 1319-1339.

Hoekstra, J., van der Goot, D. P. J., van den Brink, G., & Bilsen, F. A. (1974). The influence of the number of cycles upon the visual contrast threshold for spatial sine wave patterns. Vision Research, 14, 365-368.

Hubel, D. H. & Wiesel, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. Journal of Physiology, 206, 419-436.

Imamura, K., Richter, H., Fischer, H., Lennerstrand, G., Franzen, O., Rydberg, A., Andersson, J., Schneider, H., Onoe, H., Watanabe, Y., & Langstrom, B. (1997). Reduced activity in the extrastriate cortex of individuals with strabismic amblyopia. Neuroscience Letters, 225, 173-176.

Jackson, C. & Glasson, W. (1998). Prevention of visual loss: Screening in general practice. Australian Family Physician, 27, 150-153.

Jacobson, S. G., Mohindra, I., & Held, R. (1981). Development of visual acuity in infants with congenital cataracts. British Journal of Ophthalmology, 65, 727-735.

Kelly, D. H. (1975). How may bars make a grating? Vision Research, 15, 625-626.

Leguire, L. E., Rogers, G. L., & Bremer, D. L. (1990). Amblyopia: The normal eye is not normal. Journal of Pediatric Ophthalmology and Strabismus, 27, 32-38.

Lennerstrand, G. & Ahlström, C. O. (1989). Contrast sensitivity in macular degeneration and the relation to subjective visual impairment. Acta Ophthalmologica, 67, 225-233.

Levi, D. M. & Klein, S. A. (1992). The role of local contrast in the visual deficits of humans with naturally occurring amblyopia. Neuroscience Letters, 136, 63-66.

Lewis, T. L. & Maurer, D. (1992). The development of the temporal and nasal visual fields during infancy. Vision Research, 32, 903-911.

Lloyd, I. C., Dowler, J. G. F., Kriss, A., Speedwell, L., Thompson, D. A., Russell-Eggitt, I., & Taylor, D. (1995). Modulation of amblyopia following early surgery for unilateral congenital cataracts. British Journal of Ophthalmology, 79, 802-806.

Loeffler, M., Wise, J., & Gans, M. (1990). Contrast sensitivity letter charts as a test of visual function in amblyopia. Journal of Pediatric Ophthalmology and Strabismus, 27, 32-38.

Mäntyjärvi, M. I., Autere, M. H., Silvennoinen, A. M., & Myöhänen, T. (1989). Observations on the use of three different contrast sensitivity tests in children and young adults. Journal of Pediatric Ophthalmology and Strabismus, 26, 113-119.

Maurer, D. & Lewis, T. L. (1993). Visual outcomes after infantile cataract. In K. Simons (Ed.), Early Visual Development: Normal and Abnormal (pp. 454-484). New York: Oxford University Press.

Maurer, D., Lewis, T. L., & Brent, H. P. (1989). The effects of deprivation on human visual development: Studies of children treated for cataracts. In F. J. Morrison, C. Lord, & D. P. Keating (Eds.), Applied Developmental Psychology. Vol 3. Psychological Development in Infancy (pp. 39-227). San Diego: Academic Press.

Maurer, D., Lewis, T. L., Brent, H. P., & Levin, A. V. (1999). Rapid improvement in the acuity of infants after visual input. Science, 286, 108-110.

Mayer, D. L. & Dobson, V. (1982). Visual acuity development in infants and young children, as assessed by operant preferential looking. Vision Research, 22, 1141-1151.

McDonald, M. A., Dobson, V., Sebris, L., Baitch, L., Varner, D., & Teller, D. Y. (1985). The acuity card procedure: A rapid test of infant acuity. Investigative Ophthalmology and Visual Science, 26, 1158-1162.

Mitchell, D. E., Murphy, K. M., & Kaye, M. G. (1984). Labile nature of visual recovery promoted by reverse occlusion in monocularly deprived kittens. Proceedings of the National Academy of Science, 81, 286-288.

Mohn, G. & van Hof-van Duin, J. (1986). Development of the binocular and monocular visual fields of human infants during the first year of life. Clinical Vision Science, 1, 51-64.

Mohn, G. & van Hof-van Duin, J. (1991). Development of spatial vision. In D. Regan (Ed.). Vision and Visual Dysfunction. Vol. 10. Spatial Vision (pp. 179-192). London: Macmillan.

Norcia, A. M. & Tyler, C. W. (1985). Spatial frequency sweep VEP: Visual acuity during the first year of life. Vision Research, 25, 1399-1408.

Norcia, A. M., Tyler, C. W., & Allen, D. (1986). Electrophysiological assessment of contrast sensitivity in human infants. American Journal of Optometry and Physiological Optics, 63, 12-15.

Norcia, A. M., Tyler, C. W., & Hamer, R. D. (1988). High visual contrast sensitivity in the young human infant. Investigative Ophthalmology and Visual Science, 29, 44-49.

Norcia, A. M., Tyler, C. W., & Hamer, R. D. (1990). Development of contrast sensitivity in the human infant. Vision Research, 30, 1475-1486.

Odom, J. V., Hoyt, C., & Marg, E. (1981). Effect of natural deprivation and unilateral eye patching on visual acuity of infants and children. Archives of Ophthalmology, 99, 1412-1416.

Orel-Bixler, D., Haegerstrom-Portnoy, G, & Hall, A. (1989). Visual assessment of the multiply handicapped patient. Optometry and Vision Science, 66, 530-536.

Peterzell, D. H., Werner, J. S., & Kaplan, P. S. (1993). Individual differences in contrast sensitivity functions: The first four months of life in human infants. Vision Research, 33, 381-396.

Pirchio, M., Spinelli, D., Fiorentini, A. & Maffei, L. (1978). Infant contrast sensitivity evaluated by evoked potentials. Brain Research, 141, 179-184.

Richman, J. E. & Lyons, S. (1994). A forced choice procedure for evaluation of contrast sensitivity function in preschool children. Journal of the American Optometric Association, 65, 859-864.

Riddell, P. M., Ladenheim, B., Mast, J., Catalino, T., Nobile, R., & Hainline, L. (1997). Comparison of measures of visual acuity in infants: Teller Acuity Cards and sweep visual evoked potentials. Optometry and Vision Science, 74, 702-707.

Rogers, G. L., Bremer, D. L., & Leguire, L. E. (1987). The contrast sensitivity function and childhood amblyopia. American Journal of Ophthalmology, 104, 2156-2160.

Rovamo, J., Mustonen, J., & Näsänen, R. (1994). Modelling contrast sensitivity as a function of retinal illuminance and grating area. Vision Research, 34, 1301-1314.

Scharre, J. E., Cotter, S. A., Stein-Block, S. S., & Kelly, S. A. (1990). Normative contrast sensitivity data for young children. Optometry and Vision Science, 67, 826-832.

Schwartz, S. H. (Ed.). (1999). Spatial Vision. Visual Perception (pp. 175-204). Stamford: Prentice Hall.

Scialfa, C. T., Tyrell, R. A., Garvey, P. M., Deering, L. M., Leibowitz, H. W., & Goebel, C. C. (1988). Age differences in Vistech near contrast sensitivity. American Journal of Optometry and Physiological Optics, 65, 951-956.

Sekuler, R. & Blake, R. (1994). Spatial vision and pattern recognition. In J. Vaicunas & J. Akers (Eds.), Perception (pp. 141-179). New York: McGraw Hill, Inc,.

Sheedy, J. E., Bailey, I. L., & Raasch, T. W. (1984). Visual acuity and chart luminance. American Journal of Optometry and Physiological Optics, 61, 595-600.

Sireteanu, R., Fronius, M., & Constantinescu, D. H. (1994). The development of visual acuity in the peripheral visual field of human infants: Binocular and monocular measurements. Vision Research, 34, 1659-1671.

Sjöstrand, J. (1981). Contrast sensitivity in children with strabismic and anisometropic amblyopia. A study of the effect of treatment. Acta Ophthalmologica, 59, 25-35.

Sokol, S. (1978). Measurement of infant visual acuity from pattern reversal evoked potentials. Vision Research, 18, 33-39.

Sturr, J. F., Kline, G. E., & Taub, H. A. (1990). Performance of young and older drivers on a static acuity under photopic and mesopic luminance conditions. Human Factors, 32, 1-8.

Thylefors, B., Négrel, A. D., Pararajasegaram, R., & Dadzie, K. Y. (1995). Global data on blindness. Bulletin of the World Health Organization, 73,115-121.

von Noorden, G. K., Dowling, J. E., & Ferguson, D. C. (1970). Experimental amblyopia in monkeys. Archives of Ophthalmology, 84, 206-214.

Wali, N., Leguire, L. E., Rogers, G. L., & Bremer, D. L. (1991). CSF interocular interactions in childhood amblyopia. Optometry and Vision Science, 68, 81-87.

Waugh, S. J., & Levi, D. M. (1993). Visibility, luminance and vernier acuity. Vision Research, 33, 527-538.

Wiesel, T. N., & Hubel, D. H. (1965). Comparison of the effects of unilateral and bilateral eye closure on cortical unit responses in kittens. Journal of Neurophsyiology, 28, 1029-1040.

Appendix A

Production of the New Contrast Sensitivity Cards

Although the construction of the new CS cards was the major accomplishment of the present thesis, it was a challenging and tedious process which required approximately 10 months of pilot work. The cards were conceived by Dr. Russell J. Adams and the specific parameters (i.e., the size, contrast, and spatial frequency of the gratings, and the dimensions of the cards) were chosen by the author and Dr. Adams based upon data from other FPL studies. The necessary custom software was developed by Avery E. Earle, resident software designer and computing consultant in the Psychology Department at Memorial University of Newfoundland. All necessary measurements and recalibrations, (discussed below) were carried out by the author.

The printing of the cards proved to be a very difficult process which involved a number of steps to ensure it was reliable enough to produce cards of precise contrast. A series of stimuli was created with the custom software and then printed on several occasions. The luminance of the stimuli was measured several times, compared, and the software was recalibrated. These steps were repeated with continued refinements over the next 8 months. In all, between 2500 and 3000 closely controlled luminance measurements and 6 recalibrations were necessary before the printing process was considered reliable. Next, the cards were printed by the Memorial University of Newfoundland Printing Services under tightly monitored conditions, and then closely inspected by the author who discarded those which contained imperfections (e.g., incorrect luminance levels, roller marks from the image setter, etc.). Following this inspection, the cards were heat pressed onto millboard by the Memorial University of Newfoundland Photographic Services. Finally, the contrast levels of the cards were verified with a spot photometer and a peephole was drilled into each one.

Appendix B

Consent Form

CONSENT FORM

I agree to allow my child ____________________ to participate in a research project on the development of vision to be conducted at Memorial University of Newfoundland. I understand that my child will view a series of gratings on vision cards in order to assess his/her contrast sensitivity. I understand that my child's participation is voluntary, that I will be present during the procedure, and that I may withdraw him/her from the project at any time. I understand that my child's performance will be confidential, that he/she will not be identified in any published report of the study, and that the results of the project will be made available to me upon its completion.

Date: ________________

Signed: ________________________