EARLY TELLER ACUITY CARD ESTIMATES AS PREDICTORS OF LONG-TERM VISUAL OUTCOME IN CHILDREN WITH PERINATAL COMPLICATIONS

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Early Teller Acuity Card Estimates as Predictors of Long-Term Visual Outcome in Children with Perinatal Complications

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Abstract

In a previous study (Adams, Courage, Byars, & McKim, 1994), the Teller Acuity Cards (TAC) were used to assess binocular grating acuity in 349 infants between 2 and 42 months (M = 13.20 months, SD = 11.65). All of these children were at risk for abnormal visual/neurological development due to preterm birth and/or significant perinatal complications (e.g., birth asphyxia, seizures, respiratory distress syndrome). In the present study, 76 of these children were reassessed several years later with the TAC, as well as with a battery of spatial and non-spatial vision tests (M age at follow-up = 78.05 months, SD = 34.37, range: 35-122 months). Results of this assessment showed: (1) Compared to healthy, age-matched control children (n = 61) tested with the same battery of follow-up tests, at-risk children had consistently lower test scores, and a higher incidence of ocular disorders and refractive errors. However, most of these visual deficits were not serious. (2) Non-statistical analyses *suggest* that children who experienced perinatal seizures, bronchopulmonary dysplasia, pneumothorax or necrotizing enterocolitis had relatively poorer visual outcomes than children with other risk factors. (3) Correlational analyses show that an early measure of grating acuity was unrelated to follow-up grating acuity, nor to any other later measure of spatial or non-spatial vision. However, when both the early and follow-up results were *categorized* as either 'normal' or 'abnormal', an early TAC result did have high *normal* predictive value and *specificity*, but low *abnormal* predictive value and *sensitivity* for identifying children

with and without visual disorders. These data imply that children who experienced significant perinatal risk factors are at some risk for mild, long-term visual deficits. However, predictions based upon a single estimate of Teller acuity must be made with caution, even when the initial results are normal.

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Dedications

This thesis is dedicated to the memories of my grandfather, Hugh Coady (June 4, 1920-October 27, 1997) and my uncle, Ross Carpenter (March 30, 1941-November 3, 1997), both of whom I lost very suddenly during the course of my Masters program. Thank you for teaching me the value of family, unconditional love and faith in a Higher Power. You are forever in my heart and soul.

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Table of Contents

List of Tables

List of Figures

List of Appendices

Early Teller Acuity Card Estimates as Predictors of Long-Term Visual Outcome in Children with Perinatal Complications

It is well documented that infants who are very premature (< 32 weeks gestation) and those who are very low birth weight (VLBW; < 1501 grams) are at a higher risk for developing a variety of chronic medical, cognitive, sensory (particularly visual), motor, developmental and/or other neurological disorders (e.g., cerebral palsy, spasticity) than are healthy, full-term infants (Blackburn, 1995; Courage & Adams, 1997; Dowdeswell, Slater, Broomhall, & Tripp, 1995; Gibson, Fielder, Trounce, & Levene, 1990; McGinnity & Bryars, 1992; Pinto-Martin, Dobson, Cnaan, Zhao, & Paneth, 1996; Powls, Botting, Cooke, Stephenson, & Marlow, 1997; Stjernqvist & Svenningsen, 1993; Usher, 1987; van Hof-van Duin, Evenhuis-van Leunen, Mohn, Baerts, & Fetter, 1989; Veen et al., 1991; Weisglas-Kuperus et al., 1993). Moreover, studies have also established a solid connection between abnormal development during infancy/childhood and *specific* perinatal complications such as asphyxia (Lambert, Hoyt, Jan, Barkowich, & Flodmark, 1987; van Hof-van Duin & Mohn, 1984), intraventricular haemorrhage (IVH) (Harvey, Dobson, Luna, & Scher, 1997; McGinnity & Halliday, 1993; van Hof-van Duin & Mohn, 1984; Powls et al., 1997), seizures (McGinnity & Halliday, 1993), bronchopulmonary dysplasia (BPD) (Brown, Biglan, & Streravsky, 1990; Byars, 1994; McGinnity & Halliday, 1993) and pneumothorax (Byars, 1994). Although these conditions are very common among infants of extreme prematurity and very low birth weight, medical advances have

enabled an increasing number of infants to overcome the *immediate* survival and health-related concerns associated with perinatal complications. As such, many clinicians and researchers have shifted their efforts and intervention strategies toward *long-term* neuro-developmental outcome, including the development of the at-risk infant's visual system. Of particular concern is the impact of perinatal risk factors on functional vision throughout infancy and childhood, as vision is particularly sensitive to neurological dysfunctions.

Common Vision Problems: Associated Risk Factors and Long-Term Outcome

Infants who experience complications at or around the time of birth are at an increased risk for delayed or abnormal visual development which, under certain circumstances, may lead to permanent visual impairment. Some of the most common ophthalmological problems experienced by children who were premature and/or of very low birth weight include retinopathy of prematurity (ROP) (Dobson & Quinn, 1996; Gibson et al., 1990; Keith & Kitchen, 1983; Laws et al., 1992; Mohn & van Hof-Van Duin, 1986; Ng, Fielder, Shaw, & Levene, 1988), myopia (Fielder & Quinn, 1997; Laws et al., 1992; Mohn & van Hof-van Duin, 1986; Quinn et al., 1998; Quinn et al., 1992), astigmatism (Gibson et al., 1990), strabismus (Cats & Tan, 1989; Fledelius, 1976; Mohn & van Hof-van Duin, 1986; van Hof-van Duin et al., 1989), amblyopia (Cats & Tan, 1989) and reduced visual fields (Harvey et al., 1997; Luna, Dobson, Scher, & Gutherie, 1995; van Hof-van Duin et al., 1989; van Hof-van Duin & Mohn, 1986).

As mentioned previously, the onset and severity of many of these visual dysfunctions are associated with the presence of significant perinatal risk factors. For example, visual acuity deficits are linked with the occurrence of BPD (Adams, Courage, Byars, & McKim, 1994; Courage & Adams, 1997; Luna, Dobson, & Gutherie, 1992), seizures (McGinnity & Halliday, 1993), a combination of asphyxia and central nervous system (CNS) abnormalities (Luna et al., 1995), pneumothorax, and/or low head circumference (Adams et al., 1994). Strabismus is correlated with the occurrence of IVH (McGinnity & Halliday, 1993; Tamura & Hoyt, 1987), very low birth weight (Keith & Kitchen, 1983; van Hof-van Duin et al., 1989), BPD, necrotizing enterocolitis (NEC) and/or cystic periventricular leucomalacia (McGinnity & Halliday, 1993). Furthermore, VLBW, NEC and a history of heavy maternal smoking during pregnancy are all associated with regressed ROP (McGinnity & Halliday, 1993). And finally, significant relationships exist between reduced visual fields and VLBW (van Hof-van Duin et al., 1989) and/or a combination of asphyxia and CNS abnormalities (Luna et al., 1995). Unfortunately, because these risk factors often appear simultaneously, or are affiliated with a number of conditions, it is very difficult to determine which individual complication may have the strongest impact on visual development, and which factor(s) may lead to long-term deficits or complications (Courage & Adams, 1997).

In an attempt to determine the *long-term* impact of perinatal risk factors and abnormal early visual development, researchers have studied the visual outcome of

children at various stages of development. For instance, studies show that as many as 73% of at-risk VLBW infants have some form of visual impairment at 6 months of age (Weisglas-Kuperus et al., 1993), 29% to 33% still experience impairments at 1 year of age (van Hof-van Duin et al., 1989; Weisglas-Kuperus et al., 1993), and approximately 28% of VLBW infants have visual impairments at 2.5 years of age (Weisglas-Kuperus et al., 1993). In a study of older children (M = 9.1 years, SD = 1.05), 19% have a strabismus (versus 2.5% of controls), 7% show signs of regressed ROP (versus 0% of controls) and, as a group, the VLBW children are more myopic than control children of normal birth weight (M = −1.67 D versus −0.99 D). Furthermore, only 89.5% of the VLBW children have binocular acuities of 20/20 (corrected) or better, versus 98% of the normal birth weight children. On the other extreme, 5% of the VLBW children (versus 0% of controls) have a binocular acuity estimate of 20/60 (corrected) or worse (McGinnity & Bryars, 1992; McGinnity & Halliday, 1993). Similarly, in a group of still older 11 to 13-year-old children (n = 137) who were VLBW infants, 10% have a detectable strabismus, 15% wear corrective lenses for myopia, and as many as 30% show deficits on tests of contrast sensitivity and stereopsis (Powls et al., 1997) at the time of testing. Overall, these outcome studies suggest that there is a delay in visual system maturation in at-risk VLBW populations, and that some problems do persist well into childhood and adolescence. However, studies have generally focused on structural anomalies within the visual system, and not visual functioning.

Assessment of Functional Vision in At-Risk Infant Populations

Research concerning *functional* vision outcomes in at-risk infants has generally focused on the development of visual acuity because, traditionally, this has been the most common single measure of visual functioning. To gain a better understanding for how visual acuity measurement techniques have changed to accommodate younger patients, this section will describe the evolution of visual acuity assessment in pre-verbal children. Specifically, visual acuity is a measure of the maximal capacity of the visual system to resolve small detail at high contrast. In adults, *recognition acuity* is estimated with the familiar Snellen ("Big E") eye chart. The patient is required to read a series of increasingly smaller letters on the chart until he or she is no longer able to accurately identify them. On average, this test can be completed in about 1-2 minutes per eye. However, because of the language and attentional skills necessary to complete a recognition acuity test, such measures are inappropriate for assessing infants (and very young children). Therefore, alternate testing methods have been devised for testing visual acuity in young children. For example, infant *resolution* or *grating acuity* is generally assessed with black-and-white sine- or square-wave gratings. These gratings appear as patches of alternating black-and-white stripes, with each patch containing stripes of a particular thicknesses (i.e., a particular spatial frequency). In most cases, each grating is paired with a second unpatterned patch of equal space-average luminance. During the assessment, if the infant is able to resolve the grating, he/she will prefer to look at the patterned stimulus over the

unpatterned stimulus (i.e., he/she will look at it longer/more often).

With the use of gratings, researchers have developed a variety of reflexive, electrophysiological, and behavioural techniques to assess resolution acuity in infants and young children (for reviews see Dobson & Teller, 1978; McDonald, 1986; Simons, 1983). The first class of techniques relies on the participant's innate visual reflexes and measures the optokinetic nystagmus (OKN) response. A series of moving black-and-white stripes are presented in front of the participant while an examiner (or a set of electrodes attached around the eyes) records the eye movements. If the visual system detects the stripes, the eyes slowly follow the stimuli in the same direction that they are moving, and periodically refixate rapidly in the opposite direction. If the visual system is not able to detect the stripes, OKN will not occur. The examiner begins the assessment with the widest stripes (lowest spatial frequency) and continues with successively smaller stripes (higher spatial frequencies) on subsequent trials. The spatial frequency of the smallest stripes that can reliably elicit OKN is taken as an estimate of the participant's grating acuity. This technique has been used successfully with young children and infants, including premature/VLBW children (Allen & Capute, 1986; Cioni et al., 1997; D'Agostino et al., 1997; Gibson et al., 1990; Manny & Fern, 1990; van Hof-van Duin et al., 1998). Unfortunately, OKN is affected by participant fatigue and inattentiveness, and the apparatus used in the procedure is often very large and cumbersome, thus making it an unlikely choice for widespread clinical use.

A second set of techniques consists of measurements of electrophysiological responses from the CNS, namely visually-evoked potentials from the visual cortex (VEP). VEPs are elicited by placing a patterned stimulus (e.g., a checkerboard or grating) in front of the participant. Electrodes on the participant's scalp record the (averaged) electrical responses of the visual cortex to the stimulus. Like OKN, an acuity estimate is made based on the smallest check/stripe that elicits a reliable response (i.e., the smallest recordable amplitude). This method has also been used successfully with young children and infants, including premature infants (Gottlob et al., 1990; Kos-Pietro et al., 1997; Placzek, Mushin, & Dubowitz, 1985). Moreover, unlike OKN, this method is not as severely limited by participant inattentiveness. Unfortunately, VEP tends to *overestimate* visual acuity (Riddell et al., 1997). Furthermore, a typical VEP assessment requires significant technical training and the use of sophisticated equipment, factors which makes it unsuitable for extensive clinical use.

Traditionally, the most common method used to estimate visual acuity in non-verbal children has been forced-choice preferential looking (FPL). Unlike OKN and VEP, this behavioural technique assesses resolution (grating) acuity by relying on an infant's innate visual preference for a patterned over an unpatterned stimulus, when both are presented simultaneously (Fantz, 1958). In most versions of FPL, an examiner, who is blind to the location of the grating pattern, makes a judgment about its location by relying on the assumption that if the child can resolve the grating, then he or she will

prefer to fixate on it. As with the previous techniques, an estimate of visual acuity is based upon the smallest resolvable grating. Unfortunately, due to the large number of trials involved (i.e., 20 or more per spatial frequency) and the accompanying attentional demands placed on young children, traditional FPL techniques have not gained widespread acceptance in clinical settings (McDonald et al., 1985; McDonald, Sebris, Mohn, Teller, & Dobson, 1986; Teller, 1983; Teller, McDonald, Preston, Sebris, & Dobson, 1986).

A recent modification of the FPL procedure overcomes most of these disadvantages. The Teller Acuity Card (TAC) procedure (McDonald et al., 1985) consists of square-wave gratings mounted on lightweight, hand-held cards. Testing begins with a coarse, low frequency grating and progresses to finer gratings of higher spatial frequencies. On each trial, a trained observer, naïve to the location of the grating, makes an assessment of the child's preferential looking behaviour (e.g., direction and/or strength of eye and/or head movements), again relying on the assumption that the child will prefer the grating stimulus over the blank patch on each card. Each spatial frequency is quickly retested for as long as is necessary for the observer to make a confident decision about the location of the target stimulus. This method allows the observer to incorporate a great deal of information about the child's response into his or her judgment; information that would normally be overlooked in fixed-trial, traditional FPL procedures (McDonald et al., 1985; Mohn, van Hof-van Duin, Fetter, deGroot, & Hage,

1988; Teller et al., 1986). Testing progresses with gratings of increasing spatial frequency and stops when the child shows no clear preference for either side of a card. An estimate of resolution acuity is based upon the highest resolvable spatial frequency. The entire procedure can usually be completed in about 5 to 10 minutes, versus 1 to 2 hours for FPL procedures, and is suitable for very young children, including newborn infants (Courage & Adams, 1990; McDonald, 1986; McDonald, Ankrum, Preston, Sebris, & Dobson, 1986; McDonald & Chaundry, 1989).

Unlike previous techniques, the more time-efficient TAC procedure also has high success rates for monocular (range: 66-100%; $\underline{M}$ = 89.6%, $\underline{SD}$ = 11.2) and binocular tests (range: 86-100%; $\underline{M}$ = 94.4%, $\underline{SD}$ = 5.9) (Courage & Adams, 1997; Fielder & Moseley, 1988; Hertz, 1987; McDonald et al., 1986; Mohn et al., 1988; Preston, McDonald, Sebris, Dobson, & Teller, 1987; Schmidt, 1991; Sebris, Dobson, McDonald, & Teller, 1987; Vital-Durand & Hullo, 1989). Several studies have also shown that acuity estimates obtained with the TAC are comparable to previously established norms obtained with traditional FPL techniques (McDonald et al., 1985; Teller et al., 1986), and that the procedure has demonstrated consistently high inter-observer (Dobson, Carpenter, Bonvalot, & Bossler, 1990; Hertz, 1987; Hertz & Rosenberg, 1988; Mash, Dobson, & Carpenter, 1995; McDonald et al., 1985) and intra-observer reliabilities (Hertz & Rosenberg, 1988; Mash & Dobson, 1995; McDonald et al., 1985). The TAC has also proven to be useful for assessing other pre-verbal and multi-handicapped participants who were previously

thought to be untestable (Adams & Courage, 1990; Courage & Adams, 1990; Courage, Adams, Reyno, & Kwa, 1994; Hertz & Rosenberg, 1988; McDonald et al., 1985; Mohn et al., 1988; Preston et al., 1987; Teller et al., 1986). For these practical and statistical reasons, the TAC has gained international recognition as a time-efficient, reliable, and effective assessment tool for widespread use in paediatric clinical settings.

Predictive Characteristics of the TAC and Forced-Choice Preferential Looking Measures of Early Visual Acuity

Despite the clinical potential of the TAC, the long-term predictability of both TAC and FPL measures of visual acuity is still unclear. Specifically, we do not know whether a single test of grating acuity during infancy can predict the visual status of the same child at a later age. For obvious reasons, it would be of great clinical benefit to know whether an infant with poor visual acuity will continue to have poor visual acuity or other vision-related deficits later in life. Moreover, accurate prediction based upon measures during infancy could lead to earlier and more effective medical and educational-behavioural interventions, particularly for at-risk children (Boothe, Dobson, & Teller, 1985; Byars, 1994; Courage & Adams, 1997; Dobson et al., 1986).

Several studies have attempted to evaluate the predictive characteristics of visual acuity measured by FPL and, more recently, the TAC. These studies have generally followed one of two formats, or some combination thereof: (1) long-term reliability studies which have considered whether early TAC or FPL acuity estimates predict later

TAC or FPL acuity, respectively, and (2) predictive validity studies which have considered whether early TAC or FPL acuity estimates predict later measures of recognition acuity. To date, results from these studies have been mixed. In a longitudinal study of 27 healthy, full-term infants, Courage and Adams (1990) demonstrate that early binocular TAC acuity estimates do not predict later TAC acuity estimates, at least not when estimates are obtained before the first year of age. This pattern of results is also reported by Atkinson and Braddick (1988), who used FPL to test over 100 healthy infants with a family history of amblyopia and/or strabismus. In contrast, with clinical populations (e.g., infants with cortical visual impairment, ROP, and/or preterm birth), studies show good long-term reliability for monocular FPL estimates obtained between the first and second postnatal year and those obtained up to 6 years later (Birch & Bane, 1991; Birch & Spencer, 1991). Furthermore, in a follow-up study of 45 full-term children, Saunders, Westall, and Woodhouse (1996) report that children with normal monocular FPL estimates during the first year of life tend to maintain their normal visual status, whereas visual outcome for those children with abnormal early FPL estimates is less consistent.

In addition to these test-retest reliability studies, researchers have also been interested in the predictive validity of a relatively early test of grating acuity. Two separate studies have examined FPL acuity in children who have undergone surgery to remove a congenital cataract. Maurer, Lewis, and Brent (1989b) show that monocular

FPL estimates at 12, 30, and 36 months of age are predictive of Snellen acuities at 5+ years of age. Similarly, Birch, Swanson, Stager, Woody, and Everett (1993) report good predictive validity between monocular FPL at 36 and 48 months and recognition acuity at 5+ years. However, both studies find contradictory results for acuities obtained at 24 months. Maurer et al. show that FPL estimates at 2 years do not predict Snellen results at 5 years, whereas Birch and her colleagues show a significant correlation between early FPL estimates and later contrast sensitivity and recognition acuity measures. This difference between studies may be accounted for by the short attention span of 1.5 to 2.5-year-old participants, rather than by their actual visual status. Studies have shown that children around this age are very difficult to test and there have been numerous reports of high variability and low interobserver reliability with this age group (Getz, Dobson, & Luna, 1992; Mash & Dobson, 1998; Mash, Dobson, & Carpenter, 1995).

In a more recent study, Mash and Dobson (1998) measured *both* the long-term reliability and the predictive validity of the TAC. Monocular grating acuity estimates were obtained from 129 at-risk children at 4, 8, 11, 17, 24, 30, and 36 months of age. Follow-up results show that all early monocular TAC scores correlated significantly with TAC and HOTV recognition acuity scores at 48 months (range of r: .19 to .59 and .22 to .61, respectively), with the exception of the 17 month TAC estimate (r = .13), again a result which may be attributable to the attentional capacities of children at this age. However, the proportion of variance that was accounted for by the earlier TAC scores was

relatively low (M = 9.6% and 13.9%, for TAC2 and HOTV respectively), especially for children 24 months of age and younger (M = 4.4% and 8.5%, respectively). Therefore, in addition to estimates of long-term reliability and predictive validity, Mash and Dobson also measured the *predictive value* of the TAC. For the purposes of their study, predictive value is a numerical estimate (expressed as a proportion) of the confidence a tester can have that a child with a *normal* early TAC result will show *normal* acuity at follow-up, or that a child with an initially *abnormal* TAC result will demonstrate *abnormal* acuity at follow-up. Results of this assessment show that the predictive values are higher for those infants who obtained normal results on the first TAC test, compared to those children who fell initially within the abnormal range (range: .73 to .84 for normal, versus .39 to .69 for abnormal). Similar to the findings of Saunders et al. (1996), this study suggests that children who score within the normal range during infancy/early childhood tend to score in the normal acuity range at follow-up, whereas children with initially abnormal acuity tend to have less predictable patterns of visual development.

In the most comprehensive study to date, Dobson et al. (1999) obtained monocular TAC grating acuity estimates from 575 children ('normal' group) at 1 year of age. Another 111 children ('blind' group) were also tested, but no measurable TAC estimates could be obtained. Similar to Mash and Dobson (1998), low but significant correlations are found between TAC measures taken during infancy and follow-up TAC and Snellen measures taken at 5.5 years of age, however, they account for only 3%

(Snellen) and 13% (TAC) of the variability between the 1 year and 5.5 year acuity estimates. Again, the more clinically-relevant measures of predictive value showed that children who had normal visual acuity at 1 year of age also had normal TAC and Snellen acuities at 5.5 years (94.3% and 86.8%, respectively). Unfortunately, small sample sizes did not allow for the calculation of abnormal predictive values. However, it is noted that children who showed no measurable acuity during initial testing continued to have a very poor prognosis for any quantifiable vision later in life.

The Current Study

Although significant strides have been made (e.g., Dobson et al., 1999; Mash & Dobson, 1998), the existing literature regarding long-term visual outcome in at-risk infant populations focuses primarily on the incidence and progression of structural ocular disorders (e.g., ROP, strabismus), and/or on measures of visual acuity. Overall, findings have been mixed or inconclusive and many studies have been criticized for having one or more obvious shortcomings (e.g., small sample sizes; short test-retest intervals; participants in only one age range; assessment of a small array of visual functions; use of age-inappropriate tests; for a review, see Mash & Dobson, 1998). Furthermore, there has been a general lack of long-term investigations to address the overwhelming evidence that in *addition* to acuity loss, these children are at risk for a *variety* of visual deficits (see Fielder, Foreman, Moseley, & Robinson, 1993).

In the present research, we attempt to overcome these shortcomings by using

age-appropriate tests to evaluate a *wide variety* of visual functions in a very *heterogeneous* sample of at-risk children. More specifically, we attempt here to follow-up a large group of at-risk infants (n = 349) who were first tested with the Teller Acuity Cards between the ages of 2 and 42 months[1] (Adams et al., 1994). In this follow-up, a representative subsample (n = 76) of the original group (now between 2 and 10 years) is retested with the TAC, as well as with an extensive battery of spatial and non-spatial vision tests (i.e., contrast sensitivity, recognition acuity, resolution acuity, colour vision, peripheral vision, stereoacuity, binocular alignment/ ocular motility, gross astigmatism). Results from the original and follow-up tests are compared in order to answer three specific research questions: (1) What is the long-term visual outcome of a heterogeneous group of at-risk infants who experienced a variety of perinatal complications? (2) What influence, if any, do individual perinatal risk factors have on visual outcome? (3) Can a single estimate of grating acuity during infancy predict long-term functional vision? More specifically, does a 'normal' result during infancy predict a 'normal' result in childhood, and does an 'abnormal' result during infancy predict an 'abnormal' result in childhood. To date, this research represents the most thorough examination of the outcome of functional vision in at-risk infants, both in terms of the age range of the children and the extensiveness of the vision test battery. Furthermore, by evaluating the degree to which test results remain consistent over time, we will have conducted the most comprehensive investigation of the predictive ability and clinical utility of a relatively early estimate of

grating visual acuity.

Method

Participants

Participants were 76 children (38 males, 38 females), between the ages of 35 and 122 months (M = 78.1 months, SD = 24.4), obtained (see details below) from a larger group of 349 infants who were assessed in a previous study (Adams, Courage, Byars, & McKim, 1994). At birth, all children had been designated as 'at-risk' and were referred to the Provincial Perinatal Program (PPP) in St. John's, Newfoundland, Canada. This program is operated by the Charles A. Janeway Child Health Centre and is designed to provide regular, postnatal developmental/medical assessments of at-risk infants. Children are enrolled in the PPP if they meet one or more of the following criteria: (1) birth weight less than or equal to 1500 grams; (2) significant neurological signs that persist beyond the first six hours after birth; (3) neonatal seizures; (4) an Apgar Score of five or less at 5 minutes; (5) a head circumference two standard deviations below the mean at birth and remaining so at the time of discharge from the hospital; (6) significant hypoglycaemia; (7) significant metabolic acidosis at birth (cord blood ph less than 7.20 and a bicarbonate value of less than 14 or a base excess value in excess of −12). Participants in the present sample had a mean gestational age of 35.3 weeks (SD = 4.8) and a mean birth weight of 2416.3 grams (SD = 996.0). All medical, perinatal, infancy, and outcome data for the at-risk group are summarized in spreadsheet form in Appendix A.

During at least one of their visits to the PPP within the first three postnatal years, all of the "at risk" children (n=349) were tested with the Teller Acuity Cards (TAC; see description below). This initial testing took place between 1990 and 1995. At the time of testing, the mean age of the children was 13.2 months (SD = 11.7; range: 2-42 months). For the current study, eligible participants were screened by a third party employed at the PPP, and a list of contact names was provided. Participants were then recruited for the follow-up phase of the study based upon an exhaustive search of their local availability and the accessibility of their current phone numbers. After contacting the parents of the 102 children who were still in the area, 79 appointments were made and 76 were attended. The remaining 23 children could not participate due to parental work schedules (i.e., shift work), involvement in extracurricular activities, and/or lack of transportation into the city.

In addition, an age-matched "control" sample of 61 healthy, full-term children (31 males, 30 females) was recruited by word of mouth and tested with the same procedure as that used with the at-risk sample. At the time of testing, this control group had a mean age of 84.7 months (SD = 25.3), and at birth, they had a mean gestational age of 39.9 weeks (SD = 1.0) and birth weight of 3654.5 grams (SD = 469.7).

Ophthalmic History

During the years prior to the present assessment, 49 of the 76 at-risk children had undergone an ophthalmological examination. Records and information from the latest

exams were obtained for 40 (81.6%) of these children. The records for the other nine (18.4%) children were either in permanent storage, or the eye care specialist could not be reached. Among the 40 children for whom records were available, 15 (37.5%) of the children were diagnosed with one or more of the following conditions of note: significant, but correctable, refractive error [hyperopia greater than or equal to +2.00 diopters (D) spherical equivalent (n = 4), myopia greater than or equal to −2.00 D spherical equivalent (n = 4), astigmatism greater than or equal to 2.00 D (n = 5) and/or anisometropia (spherical equivalent) greater than 2.00 D (n = 1)]. The following conditions were not/ could not be corrected: amblyopia (n = 4); abnormal stereo vision (n = 4); strabismus (n = 8); nystagmus (n = 3); overactive inferior oblique muscles (n = 4); and/or red-green colour deficiency (n = 1). Eight (13.1%) of the 61 control children had previously undergone an ophthalmic exam. According to the records obtained, only one participant required mild corrective lenses (+1.25 D). Otherwise, there were no significant diagnoses made, nor abnormalities observed for these control children.

General Procedure

This experimental protocol was approved by the Memorial University Faculty of Science Human Ethics Committee and each parent/guardian provided written consent before testing took place (see Appendix B). Although formal (i.e., written) consent was not provided by the children (due to developmental and maturity constraints), the researcher made a conscious effort no ensure that all participants were aware that they

could discontinue participation, without consequence, at any time. At the beginning of the testing session, the experimenter took a brief ophthalmic and general medical history for each child. In order to augment and verify the ophthalmic information provided, parents were asked to give written permission for the experimenter to contact any eye care specialist that the child had seen in the past (see above). Parents also voluntarily completed a brief questionnaire that enquired about their child's educational history, level of academic achievement, as well as the total income of the family (to estimate socio-economic status). Copies of this form and the ophthalmic/medical history form are provided in Appendices C and D. A copy of the letter and form sent to the eye care specialist are provided in Appendices E and F.

Every participant was evaluated with 12 vision tests, each of which was designed for preschool and early school-age children. This battery of tests was used to assess seven major areas of the participant's visual status: visual acuity, contrast sensitivity, stereoacuity, peripheral vision, colour vision, astigmatism and binocular alignment. Participants completed the tests in a 3.8 x 3.0 m lab under bright lighting conditions (illumination: ≈300 lux; General Electric F40-C75 fluorescent tubes) and at a correlated colour temperature (6500°K) recommended for colour vision testing. The experimenter attempted to present the tests in an order and at a rate that was appropriate for the attentional level of each participant. If corrective lenses were prescribed for a participant, he or she was instructed to wear them during the testing session. Each participant's test

results were recorded on a single data sheet (see Appendix G).

Visual acuity tests: Recognition acuity. Both near (40 cm) and distance (3 m) recognition acuity estimates were determined for each participant. The procedure was conducted at two distances to help differentiate whether any observed acuity deficits were due to myopia (nearsightedness) or hyperopia (farsightedness). Acuity estimates were obtained with three standard types of recognition tests; Snellen letter charts (the 'Big E' charts), Tumbling E charts (also termed by some as 'The Illiterate E'), and the Broken Wheel test. All charts and tests were printed on matte, white plastic boards of varying size. The Snellen and Tumbling E charts had targets arranged in rows of decreasing size, whereas the Broken Wheel test consisted of pairs of cards, with one card in each pair containing a Landolt C target of a given size (see Appendices H and I for examples). The Snellen letter charts were used with those older participants (e.g., ≥ 5 years of age) who could identify the name of each letter. The Tumbling E charts were used with younger (e.g., < 5 years of age) or with non-verbal participants who could indicate (with a verbal response or hand gesture) the appropriate orientation (right, left, up or down) of each target 'E'. For all tests, participants were first evaluated with the largest targets, and then tested with progressively smaller targets, until he or she made two or more identification errors with targets of a given size. The size of the smallest target(s) that the participant could reliably detect was taken as an estimate of his/her acuity threshold. All tests were attempted under binocular viewing conditions and both

the Snellen and Tumbling E were tested monocularly.

For the near tests (Tumbling E and HOTV), participants were seated at a viewing distance of 40 cm and the charts were presented on an adjustable stand (Fellowes Inc., Itasca, IL). The 14 cm X 20.5 cm Tumbling E chart (Bernell Corp., South Bend, Ind.) consists of 11 rows of Es of varying orientations. The 9.5 cm X 18.5 cm HOTV chart (Bernell Corp., South Bend, IN) consists of seven rows of uppercase letters (H, O, T and V), arranged in a random order. From 40 cm, the Snellen equivalents of the targets on both charts range from 20/200 to 20/20. To test distance recognition acuity, participants stood at 3 m facing larger versions of the charts (Tumbling E, Snellen, or Broken Wheel), which were mounted on a larger white matteboard and suspended from a plastic, tubular flip chart stand (Bemiss-Jason Chartmaster, Newark, CA). The 23 cm X 35.5 cm distance Tumbling E chart (Good-Lite Co., Forest Park, IL.) consists of nine rows of Es of varying orientations and the 23 cm X 36 cm Snellen chart (Graham-Field Co.) consists of 11 rows of uppercase letters. From 3 m, the Snellen equivalents of the targets range from 20/120 to 20/15.

For the Broken Wheel Test of Visual Acuity (Bernell Corp., South Bend, IN), the participant was shown a pair of schematic cars on 10 cm X 20.5 cm white plastic cards and was instructed to locate the car with the gap in its wheels. The gap corresponds to a standard Landolt C optotype representing a specific acuity value (Snellen equivalents: 20/100 to 20/20). If a participant achieved an acuity level of 20/20 from the standard

testing distance of 3 m, he or she was retested at 4.5 m. If the smallest gap was still detectable at this distance (i.e., representing an acuity of 20/15), the participant was then retested with this pair of stimuli at 6 m (i.e., representing an acuity of 20/10).

Visual acuity tests: Resolution acuity. The Teller Acuity Cards (TAC; Vistech Consultants Inc., Dayton, OH) in this study were identical to those used to assess participants during infancy. The test consists of seventeen 26 x 51 cm gray cards, each with a 5 mm central peephole . Fifteen of the cards contain a 12.5 x 12.5 cm black-and-white square-wave grating which matches the gray background of the card in space-average luminance to within 1%. The grating is located to the left or the right of the peephole. Viewed from 84 cm, the targets range in spatial frequency from 0.47 to 57.0 cycles/degree (Snellen equivalents: 20/1200 to 20/10), in approximately half-octave steps (an octave is a halving/doubling of the grating's stripe size). The 16th ('low vision') card contains a larger, 26 x 23 cm grating composed of very wide stripes. The 17th 'control' card contains no grating and appears uniformly gray. The testing procedure was modeled after the instructions provided in the TAC instruction manual and is described fully in Courage and Adams (1990). To prevent room distractions, each card was presented through a 22 x 47 cm rectangular opening in a large, three panel matteboard screen that matched the card background in colour and space-average luminance.

The experimenter, positioned behind the screen, was responsible for observing the participant's responses through the peephole and, after as many trials with each card

as was necessary, making a decision about the location of the grating. The experimenter, blind to the location of the grating, presented the cards to the participant in order of increasing spatial frequency (thicker to thinner stripes). The participant was instructed to indicate the location of the grating with hand gestures (e.g., pointing) and/or with eye gazes. Testing continued until the observer judged that the participant was no longer able to detect a particular grating. The finest grating that the participant could detect was taken as an estimate of his/her visual acuity.

If the participant was able to detect the grating representing the highest spatial frequency (57.0 cpd; Snellen equivalent: 20/10) at 84 cm, he or she was retested at a viewing distance of 168 cm with the two cards representing the highest spatial frequencies (78 and 114 cpd; Snellen equivalents: 20/8 and 20/5). This retesting procedure allowed for a more precise estimate of threshold.

Contrast sensitivity. Compared to visual acuity, contrast sensitivity (CS) provides a more comprehensive evaluation of spatial vision. Contrast sensitivity estimates contrast thresholds across a *variety* of spatial frequencies. These estimations are gaining clinical significance because deviations in contrast sensitivity can reveal ophthalmological and/or neural-based dysfunctions not revealed by tests of visual acuity.

The contrast sensitivity test (Vistech Consultants Inc., Dayton, OH) used in this study consists of 45 circular sine-wave gratings (radius 3.75 cm), arranged in a five row by nine column array on a white background. Each grating is oriented vertically, or is

tilted 15° to the left or the right. From a distance of 3 m, the gratings in each row represent one of five spatial frequencies (either 1.5, 3, 6, 12 or 18 cycles/deg) and the gratings in each row decrease in contrast by about one octave steps (from ±30% to ±0.3% or CS = 3.3 to 333.3).

The participant viewed the test from a distance of 3 m and used a verbal response or hand gesture to indicate the orientation of the gratings. Row order was randomized across participants, but gratings within a row (i.e., each spatial frequency) were always tested in an order of decreasing contrast. The procedure continued until the participant indicated that he or she could no longer see the grating or until he or she made two successive mistakes within a particular row. The last grating seen/indicated was taken as an estimate of the contrast threshold for that spatial frequency.

Stereoacuity. The Stereo Fly Test (Stereo Optical Co., Chicago, IL) is designed to assess the degree of stereoscopic depth perception, an index of the development of cortical binocular cells. The participant was seated and the test was presented on an adjustable stand (Fellowes Inc., Itasca, IL) at a viewing distance of 40 cm. The participant wore a pair of polarized glasses and these were always in place before the stimuli were shown. In the event that a participant required corrective lenses, the polarized glasses were worn over them. The test contains a series of stimuli, each of which has a specific degree of crossed disparity. If seen by a participant with normal fusion, the target stimuli will appear to 'stick out' from the page. Participants were

instructed to indicate the location of these three-dimensional stimuli with a verbal response or a hand gesture. In general, testing began with a stimulus with high disparity and progressed with stimuli of lower disparity. The last stimulus detected (i.e., the stimulus representing the finest level of disparity) was taken as an estimate of the threshold of stereopsis.

Specifically, the Stereo Fly Test contains three related tests. They are, in order of increasing difficulty/precision, 1) the 'house fly' test, 2) the 'animal' test, and 3) the 'circle' test. The house fly test is first used to establish the presence of gross stereopsis (approximately 3000 seconds of arc). The participant was instructed to 'pinch' the fly's wing between his/her thumb and forefinger. If stereopsis is present, the participant's fingers remain above the plane of the picture during the task. In the absence of stereopsis, the picture appears as a flat photograph and the participant's fingers touch the surface of the picture.

In the animal test, three rows of common animal figures were presented and the target stimulus within a given row represents an approximate disparity of either 400, 200, or 100 seconds of arc. If the participant was unable to point to the location of the three-dimensional stimulus in one row, but was able to make the more difficult discrimination on the subsequent row, he or she was retested on the missed line to confirm the results on the subsequent row.

The circle test is designed to assess fine depth discrimination. It consists of nine,

4-circle clusters, with one of the circles (the target) in each cluster containing a specific degree of disparity. The participant's initial task was to identify the large-disparity target circle (800 seconds of arc) located within the first cluster, and then to proceed with clusters containing targets with lesser and lesser disparities (to a minimum of 40 seconds of arc). Testing continued until the participant made two successive mistakes or gave up. As with the animal test, retesting was used to confirm results.

Binocular peripheral vision. The Field of Vision Disk (Hubbard Scientific, Chippewa Falls, WI) is designed to assess the limits of the horizontal plane of binocular peripheral vision. While seated, the participant held the disk to his/her forehead using the handles provided and was instructed to look straight ahead at a central target. A parent observed the participant to ensure that his/her eyes remained fixated on the central target throughout the test. Standing behind the participant, the experimenter slowly moved a second peripheral target toward the front of the disk. At the onset of the trial, the peripheral target was out of view and, as the experimenter moved it inward, the participant was instructed to indicate when the target could first be seen. The test was performed twice in both the left and right peripheral fields and the average of the two measurements (in degrees) was taken as an estimate of the limit of the participant's field of binocular vision on each side. The sum of the right and left side measurements was recorded as the full range of horizontal binocular peripheral vision.

Colour vision. The 38 plate edition of the Ishihara Pseudoisochromatic Colour Plates (Kanehara and Co., Tokyo, Japan) was used to screen for the most common congenital colour vision deficiencies; protanopia, deuteranopia, protanomaly, and deuteranomaly. Although the test is designed to be viewed at a distance of 75 cm, it was necessary to modify the procedure to accommodate the younger participants. The plates were placed on a tabletop and the participant was instructed to sit as far back as was comfortable and reasonable. On average, the test distance was 60 cm (±10 cm).

Only the preschool portion of the test was used (plates 26 to 38; the 'illiterate plates'). The participant's task was to trace the winding line between two Xs on a particular plate with the paint brush provided. The experimenter watched the tracing attempts and determined if the participant was able to follow the proper line accurately. If the experimenter determined that a tracing was inaccurate, the participant was retested (when possible) with the equivalent numeral (adult) plate to confirm the response.

Gross astigmatism. A gross screening chart (Graham-Field) was used to detect astigmatism. The chart consists of a fan-like, 180° array of black lines, spaced 10° apart, on a white background. The test was mounted on a white matteboard and suspended at eye level from the flip chart stand. Testing was conducted at the standard viewing distance of 6 metres. The participant was instructed to look at the array and describe whatever he or she saw. To a participant without an astigmatism, all of the lines appear

clear, equally black and equally spaced. To a participant with an uncorrected astigmatism, lines of some orientations may be well focused, but lines of other orientations may appear "fuzzy" or unclear. Alternatively, the astigmatic lines may appear lighter or less black than others. To assist some reluctant participants, non-leading questions about the array were asked (e.g., "What colour are the lines?", "Are all the lines straight?"). If the participant responded negatively to these questions, a further explanation was sought (e.g., "Which lines are not straight?" "Which lines are fuzzy?"). The angle of any line that the participant described as unclear/abnormal was taken as an estimate of the approximate angle of the astigmatism.

Binocular alignment/ocular motility. A simple orthoptic examination was performed to assess three aspects of the participant's ocular alignment; corneal light reflection (the Hirshberg Test), convergence and tracking. For the corneal light test, a penlight was used to shine a beam of light into the participant's eyes. Normal eyes will reflect the light from the centre of both pupils, whereas displacements from centre indicate the presence of a strabismus. Esotropic (eye turns in), exotropic (eye turns out), hypertropic (eye turns up) and hypotropic (eye turns down) fixations were recorded.

To test for convergence, a figurine was mounted on the penlight and presented approximately 30 cm from the participant's eyes. The participant was then instructed to stare at the figurine as it moved toward him/her. As the object approaches, normal eyes will turn toward centre at the same rate/time. Abnormal convergence conditions (e.g.,

eyes did not turn at same time/rate; one eye turned while other did not) were recorded.

The figurine was again used to test tracking. In this case, the participant was instructed to follow the moving figurine with his/her eyes, while keeping his/her head still. To prevent any head movements in younger participants, it was sometimes necessary to hold the chin in place during the task. The figure was moved to the left, right, up and down and any tracking abnormalities were noted (e.g., both eyes did not track at the same rate; one eye didn't track beyond a certain point).

Participant/Parent Debriefing

At the end of the testing session, the experimenter provided the participants and the parents with a debriefing form (see Appendices J and K) which described the purpose of the study and the parents were encouraged to ask any questions about the study or its procedure. Parents were informed that this was not a full visual exam, but if the researchers noted abnormalities or below average performance on any of the vision tests, the parents were contacted within two weeks of the testing date by the supervisor of the research team. In the event that an additional ophthalmic exam was recommended, the parents were encouraged to contact the researchers with the results of that exam.

Results

A. Summary Statistics

i) Completion rates. Of the 76 at-risk children recruited, 36 (47%) completed the entire battery of 17 tests. However, success rates varied directly with age. For example,

none of the participants under 5 years of age were able to complete all of the tests, whereas 80% of the 8 to 10-year-olds completed the entire battery. On average, participants completed 13.5 tests (SD = 4.4; range: 2-17) and the number of tests completed increased with participant age (see Table 1). For example, Table 1 shows that 2 to 3-year-olds completed an average of 6.3 tests (SD = 2.8), whereas 9 to 10-year-olds completed 16.7 tests (SD = 0.7). Success rates also varied among the different tests. All participants were able to complete the Teller Acuity Cards (TAC), and administration of the binocular alignment exam was also highly successful with completion rates of 100%, 87%, and 95% for the reflection (Hirshberg Test), convergence, and tracking portions of the exam, respectively. Completion rates for the Broken Wheel and Ishihara tests were also high at 87% and 86%, respectively. Conversely, monocular distance acuity and peripheral vision tests had the worst rates (both 61%), with the vast majority (83%) of the incomplete tests shown by children under 6 years of age. The less than optimal completion rate for the youngest participants was likely due to the fact that the majority of the vision tests were designed for school-age children. For the most part, the reasons for a child failing to complete a test included an inability to understand the testing instructions (e.g., peripheral vision test), a short attention span (e.g., monocular distance acuity test), and/or a lack of co-operation and motivation. The average testing time for the at-risk participants was 36.2 minutes (SD = 14.3; range: 20-120 minutes).

Completion rates for the full-term control participants were similar, with 37

(61%) of the 61 participants completing all of the tests. As was the case with the at-risk participants, none of the control participants under 5 years of age were able to complete the entire battery of tests, whereas 89% of the 7-year-olds and 100% of the 9 to10-year-olds completed all the tests. On average, the control participants completed 15.3 tests (SD = 2.9; range: 2-17) and, similar to the at-risk participants, the number of tests completed increased with participant age. For example, 2 to 3-year-olds in the control group completed an average of 8.6 tests (SD = 3.9) and every 9 and 10-year-old completed all 17 tests. However, the mean testing time for the control participants was only 24.6 minutes (SD = 4.2; range: 10-35). This is lower than the mean reported for the at-risk group (36.2 minutes), likely because a few participants in the at-risk group who took well over an hour to complete the battery. Furthermore, because the control group was tested after the at-risk group, the experimenter was more familiar with the testing procedure and may have been able to administer the tests more efficiently. Overall, however, there were few differences between the at-risk and control groups' general test-taking performance.

ii) Representativeness of the at-risk sample. The 76 at-risk participants in this study were selected from a larger group of at-risk participants (n = 349) who, as 3 to 36-month-old infants/toddlers, had been assessed previously with the Teller Acuity Cards. As mentioned above, every effort was made to contact as many of the original participants as possible. However, for several reasons, it was not possible to recruit a

large number of them (e.g., telephone number no longer in service, moved out of the area during the intervening 5 years). Due to these recruitment problems, there was concern that the current group of 76 participants may represent a biased or selective sample of at-risk participants. Therefore, it was necessary to determine whether the 76 at-risk participants in the present study were actually representative of the original 349 participants.

In order to evaluate representativeness, a like number of participants (n = 76) was chosen at random from the original study group of 349, and this group was compared with the current study group on a number of critical perinatal measures. Results from t-tests showed that the groups did not differ significantly (all $p > 0.28$) on measures of birth weight (M = 2416.3 vs. 2529.7 grams), length of gestation (M = 35.3 vs. 35.8 weeks), number of risk factors (M = 2.7 vs. 2.7), number of days ventilated (M = 7.4 vs. 4.8), grade of intraventricular haemorrhage (IVH; M = 1.7 vs. 1.3; range: '1' low to '4' high), Neonatal Medical Index (NMI) classification[2] (M = 2.5 vs. 2.7; range: '1' best to '5' worst), developmental quotient during infancy (DQ; M = 99.3 vs. 105.9), age at the TAC test (M = 13.2 vs. 13.0 weeks), nor on acuity card score/classification (M = 3.9 vs. 3.9; range: '1' best to '6' worst). These results suggest that the present group was representative of the original study group (at least based on these variables) and was not an atypical or select subsample of at-risk infants.

B. Comparison of the At-Risk to the Full-Term Control Group

Each participant was administered tests of contrast sensitivity, monocular and binocular near and distance acuity (both recognition and resolution), stereoacuity/ stereopsis, colour vision, peripheral vision, gross astigmatism, and binocular alignment/ocular motility. For most of these tests, each participant's performance was classified as either "normal", "suspect" or "abnormal" for that particular visual function and for that child's respective age. However, for the Broken Wheel, colour vision, gross astigmatism, and binocular alignment exams, test results were classified only as either normal or abnormal. These classifications were made based on standardized international norms obtained from a number of sources. Appendix L provides specification of the norms/criteria used for the classification of each test. As seen in Appendix L, norms for near and distance acuity (resolution and recognition), peripheral vision, gross astigmatism, and the binocular alignment exam were based on those used in standard Canadian paediatric ophthalmology practice. Norms for the Ishihara Colour Plates (Kanehara and Co., Tokyo, Japan) and contrast sensitivity test (Vistech Consultants Inc., Dayton, OH) were obtained from the manufacturer of the test, and pass/fail criteria for the Broken Wheel test were provided by a preschool vision screening program (Preschool Enrichment Team, Inc., Holyoke, MA). Findings from previous research provided the norms for the tests of Teller grating acuity (Courage & Adams, 1990), contrast sensitivity (Courage, Piercey, & Adams, 1997), and stereoacuity/

stereopsis (Tatsumi & Tahira, 1972).

To compare the at-risk and control groups' performance on each of the vision tests within the battery, separate chi-square analyses were performed (see Table 2). Specifically, the chi-square test was used to determine whether the obtained frequencies for each classification (normal, suspect, abnormal) differed between groups. In order to overcome the problem of empty cells and low frequencies in the chi-square calculations, it was sometimes necessary to combine the suspect and abnormal results. This accounts for the majority of the analyses having $df = 1$, versus $df = 2$. The first seven tests in Table 2 (contrast sensitivity, monocular near acuity, binocular near acuity, monocular distance acuity, binocular distance acuity, TAC, and binocular 'Broken Wheel' acuity) represent measures of spatial vision, arguably the most important aspect of visual functioning. These results are the most important because they evaluate (or estimate) a participant's performance on Snellen-type tests. The Snellen charts (e.g., the 'Big E' charts) are the most commonly used for testing visual acuity in adults and are considered the 'gold standard' within ophthalmological testing. As shown in Table 2, the at-risk and control groups differed significantly on the majority of these spatial vision tests (contrast sensitivity, monocular near acuity, binocular and monocular distance acuity), as well as on tests of stereoacuity/stereopsis, monocular peripheral vision, and binocular alignment (all $p < .001$). As a group, the controls performed better on all of these tests (see Table 3 for the raw data). That is, among those who completed each test, the control group had a

significantly greater percentage of its scores in the normal range than did the at-risk group [e.g., contrast sensitivity: 91% vs. 76%; monocular near acuity (mean of left and right eyes): 99% vs. 78%; binocular distance acuity: 85% vs. 61%; monocular distance acuity (mean of left and right eyes): 63% vs. 30%; stereoacuity: 97% vs. 82%; monocular peripheral vision (mean of left and right eyes): 96% vs. 71%; binocular alignment (mean of the three tests): 98% vs. 92%]. It should be noted that although the control group performed better on the monocular distance acuity test than did the at-risk group, both groups' overall performance on this test was poor (i.e., only 63% of the control group participants and 30% of the at-risk participants who completed the test "passed" it). This may be accounted for by the participants' short attention span and/or distractibility, which is greatly affected by the use of an eye patch at the greater testing distance. The control and at-risk groups did not differ significantly on tests of binocular near acuity (100% vs. 89%), grating acuity (TAC) (98% vs. 97%), broken wheel acuity (100% vs. 97%), Ishihara Colour Plates (100% vs. 94%), or gross astigmatism (97% vs. 92%) (all $p > .05$).

C. Influence of Individual Risk Factors on Visual Outcome

Aside from comparing the visual outcome of the at-risk participants to the healthy, full-term controls', another goal of this study was to determine if specific perinatal risk factors have an impact on visual development. However, because there

were so many risk factors present among the group, we only considered those risk factors (n = 12) that were experienced by five or more participants (see Table 4). Due to low sample sizes within the risk factor subgroups, very informal analyses were used to compare the visual outcome of those participants who experienced a particular risk factor with the outcome of the at-risk group as a whole. Specifically, each subgroup was compared to the entire group on the basis of mean percentage of tests failed at follow-up, as well as on mean monocular and binocular acuity outcomes. Data for the entire at-risk group (see bottom row of Table 4 and Appendix A) show that the mean percentage of tests failed at follow-up was 18%, the mean overall monocular acuity estimate was suspect ("S"), and the mean overall binocular acuity estimate was in the low end of the normal range ("N−"). Table 4 also summarizes each risk-factors subgroup's mean failure rate and both visual acuity outcomes. For comparison purposes, a mean difference of 10% or more between the percentage of tests failed by the entire group versus the percentage of tests failed by a subgroup was considered "notable". For the acuity measures, a mean difference of two or more categories was considered notable. As shown at the end of Appendix A, mean acuity estimates are grouped into the following categories/ranges: N = normal; N− = low end of normal range; S+ = high end of suspect range; S = suspect; S− = low end of suspect range; A = abnormal.

The data in Table 4 show that the occurrence of seizures, bronchopulmonary dysplasia (BPD), pneumothorax, and/or necrotizing enterocolitis (NEC) may have been

related to higher test failure rates at follow-up (M = 31%, 28%, 35%, and 42%, respectively, versus 18% for entire at-risk group). Furthermore, the NEC subgroup also had notably lower monocular (M = A) and binocular (M = S−) acuity outcomes than the at-risk group as a whole (M = S and N−, respectively). Mean binocular acuity outcome for the BPD subgroup was also lower than the mean binocular acuity reported for the entire at-risk group (M = S versus N−, respectively). It is important to note, however, that these observations are only *suggestive*, as a much larger sample size and formal statistical analyses would be necessary before definitive conclusions can be made.

D. Correlations Between Measures Taken During the Perinatal Period, Infancy, and Childhood

i) Explanation of measures. A longitudinal summary of each at-risk participant's data is shown in Appendix A. The appendix is subdivided according to three time periods: 1) each participant's birth and risk factor information during the perinatal period is shown in the first 22 columns, from **DOB** to **NMI**; 2) his or her grating acuity performance and developmental quotient at the original testing session during infancy (ages 3 months to 3 years) are shown in the next seven columns, from **Test 1** to **z-score**; and 3) summary information about his or her overall performance on tests of grating and recognition acuity at the follow-up session during childhood (ages 3 to 10 years) are shown in the last seven columns, from **Test 2** to **Worst**.

The data shown in Appendix A represent variables which are both continuous and categorical in nature. However, perhaps the most critical continuous measure for the purpose of the present study was the participant's acuity z-score obtained during infancy. This is shown as **z-score** in the 29th column of Appendix A (range: −4.4 to 2.7) and was based on a participant's TAC score during infancy relative to established norms for his or her specific age (see Courage & Adams, 1990). This measure was of particular interest for determining whether an early TAC score can predict later acuity, particularly measures of standard recognition acuity. Other continuous variables shown in Appendix A include participant birth weight (**BW**; range: 620 to 4170g), length of gestation (**GEST**; range: 23 to 42 weeks), the number of risk factors experienced during the perinatal period (**RF**; this value represents the sum of occurrences from the previous 17 columns in Appendix A; range: 1 to 11), the developmental quotient measured during infancy (**DQ**; as assessed with the Griffith's Scales of Infant Development; range: 36 to 144), and the percentage of tests that the participant failed at the follow-up session during childhood (**% fail**; range: 0 to 60%).

The categorical variables shown in Appendix A include the participant's perinatal Neonatal Medical Index classification (**NMI**; categories: '1' best to '5' worst; see Korner et al., 1993) and his or her categorized TAC acuity estimate during infancy (**TAC1**; based on established, age-related norms from Courage & Adams, 1990; range: '1' best to '6' worst). Also included in Appendix A are conservative (i.e., worst case) evaluations of

each participant's general performance on the follow-up acuity tests. For these evaluations, each participant's visual acuity status during childhood was classified as either 'normal', 'suspect' or 'abnormal', based on the lowest estimate he or she obtained on any of the follow-up acuity measures. For example, if a participant obtained an acuity estimate in the abnormal range for one particular test, despite all other estimates being normal or suspect, he or she would be classified as "abnormal" on this worst case index. Three separate classifications were assigned to each participant, the first based upon his or her performance on all monocular acuity tests combined (**MONO**) and the second on all binocular acuity tests combined (**BINOC**). The third classification was a conservative estimate of overall acuity status and was based on the worst result that emerged when both monocular and binocular acuity estimates were combined (**WORST**).

ii) Explanation of analyses. Results from the three time periods (perinatal, infancy, and childhood) were compared to determine if measures taken at the same time agreed with each other, and if early measures correlated with later ones. However, we were perhaps most interested in determining whether perinatal results could predict results during infancy and/or childhood, and whether results during infancy could predict those at follow-up during childhood. Pairwise Pearson and Spearman correlations were calculated on a selection of perinatal (BW, GEST, RF, NMI), infancy (DQ, TAC1, Z), and childhood (%fail, MONO, BINOC, WORST) measures. Results of these analyses are shown in Tables 5 and 6, respectively. It should be noted that because

Spearman correlations measure relationships among categorical data, it was necessary to transform some of the continuous variables for the purposes of these analyses. As such, some of the categorized continuous variables found in Table 6 are not found in Appendix A. These variables include categorized birth weight (**BWCAT**; categories: '1' = 501-1000g, '2' = 1001-1500g, '3' = 1501-2000g, '4' = 2001-2500g, '5' = 2501-3000g, '6' = 3001-3500g, "7" = 3501-4500g), categorized length of gestation (**GESTCAT**; categories: '1' = 29 weeks of less, '2' = 30-32 weeks, '3' = 33-35 weeks, '4' = 36-38 weeks, '5' = more than 38 weeks), and categorized number of perinatal risk factors (**RFCAT**; categories: '1' = 1, '2' = 2, '3' = 3-4, '4' = 5-11 risk factors).

iii) Comparisons between concurrent measures. Overall, the results show that significant associations existed between most variables measured concurrently; that is, between variables measures during the same time period. The initial set of comparisons (shown roughly diagonally in Tables 5 and 6) indicate that most of the perinatal measures were correlated significantly. For example, as shown in Table 5, birth weight was positively associated with gestation ($r = .889$, $p < .0005$), and inversely related to the number of perinatal risk factors ($r = -.565$, $p < .0005$). Similarly, gestational length was inversely related to both the number of perinatal risk factors (see Table 5; $r = -.685$, $p < .0005$) and NMI classification (see Table 6; $r_s = -.307$, $p < .005$). Table 6 shows that NMI classification was positively associated with the number of perinatal risk factors ($r_s = .596$, $p < .0005$). These results support previous findings that infants with higher

birth weights are generally healthier and experience fewer complications at or around birth than infants with low birth weights. For illustration, Figure 1 shows the relationship between NMI classification and perinatal risk factor category. Although scatterplots are standard for data of this nature, many of the data points were identical, thus the results are summarized in a bar graph. For this figure, and all those subsequent, significant correlational relationships are denoted by the inclusion of the correlation coefficient (at the top of the figure), and a line of best fit (based on the raw data) has been added to help depict the direction of the relationship.

In terms of concurrent measures taken during the other time periods, the 5th column of Table 5 shows the correlation coefficient for the two measures (DQ and acuity z-score) taken at the same session during infancy. Surprisingly, this value was not significant ($r = .174$, $p = .07$). Finally, the end of the last section of Table 6 shows that all of the most important acuity-related variables at follow-up during childhood correlated with each other. For instance, overall binocular acuity was associated with both overall monocular acuity ($r_s = .562$, $p < .0005$) and worst case acuity ($r_s = .663$, $p < .0005$). Similarly, the overall monocular acuity estimate was related to the worst case acuity estimate ($r_s = .979$, $p < .0005$), a result which is not surprising, given that most of the worst case scores were based on monocular acuity results.

iv) Comparisons between measures taken during the perinatal and infant periods. Most of the middle section of Table 5 shows the correlations between perinatal and

infant measures. For example, the number of risk factors experienced during the perinatal period is inversely related to the participant's acuity z-score during later infancy ($r = -.190$, $p = .05$). To illustrate this, Figure 2 shows that infants with lower acuity z-scores generally experience more perinatal risk factors than infants with higher z-scores. Additional results in this section of Table 5 show that birth weight, length of gestation, and the number of risk factors the participant experienced during the perinatal period were all significantly correlated with DQ measured during infancy ($r = .316$, $p < .005$; $r = .388$, $p < .0005$; $r = -.315$, $p < .005$, respectively). For instance, Figure 3 illustrates that infants with higher DQs generally experience fewer risk factors at or around birth than participants with lower DQs. However, the middle section of Table 6 shows that categorized infantile grating acuity did not correlate with either birth weight, length of gestation, number of perinatal risk factors, nor NMI classification (all $p > .28$). These results suggest that DQ is a more sensitive outcome measure than the TAC, at least at this age.

v) Comparisons between measures taken during the perinatal and childhood periods. Significant positive correlations were found between birth weight and estimates of overall monocular acuity, overall binocular acuity, and worst case acuity (see first number in each of the last three columns of Table 6; $r_s = .232$, $p < .05$; $r_s = .212$, $p = .05$; and $r_s = .232$, $p < .05$, respectively). For illustration, Figures 4 and 5 show that as birth weight increases, participants' overall binocular acuity and worst case acuity outcomes improve.

Results in the top portion of the last column of Table 5 show that none of the perinatal measures (birth weight, length of gestation, nor number of perinatal risk factors) were significantly correlated with the percentage of tests that the participant failed at follow-up during childhood (all $p > .07$). For illustration, Figure 6 shows that there appears to be little relation between the mean percentage of follow-up tests failed and the length of gestation ($r = -.043$, $p = .36$).

vi) Comparisons between measures taken during the infant and childhood periods. One of the key goals of this study was to determine whether an estimate of acuity taken during infancy (notably Teller grating acuity) can predict later standard measures of childhood acuity (e.g., Snellen recognition acuity). However, as shown in the last row of Table 6, infants' grating acuity (as measured by the TAC) and all three follow-up measures of acuity during childhood did not correlate (all $p > .26$). For example, Figure 7 illustrates the lack of a significant relationship between participants' Teller grating acuity during infancy and overall binocular acuity during childhood ($r_s = -.052$, $p = .33$). Results shown at the bottom of the last two columns of Table 5 also suggest a lack of association between any of the infant and childhood measures. As illustrated in Figure 8, there is little relationship (and wide variability) between the mean percentage of tests failed at follow-up and participants' DQ during infancy ($r = -.042$, $p = .36$). Similarly, Figure 9 shows little correspondence between the mean percentage of tests failed at follow-up and participants' acuity z-score during infancy ($r = -.167$, $p = .08$). Furthermore,

Figure 10 illustrates that even when one examines only those participants at the extremes of the distribution, it appears that participants who had the highest acuity z-scores during infancy (i.e., TAC category 1 or 2) have about the same distribution of failure rates as those participants who had the lowest acuity z-scores during infancy (i.e., TAC category 5 or 6). This suggests that even extreme TAC scores (both high and low) do not correlate with long-term visual outcome.

vii) Age of participants. Results of Pearson and Spearman correlational analyses above showed that no significant correlations existed between infant and childhood measures. One possible explanation for the lack of correlations may be the wide age range (2 to 42 months of age) and the large corresponding developmental differences between participants at the time of the original TAC test. Given the rapid visual development of infants, a test score from a 2-month-old may not be as predictive of later visual functioning as a score from a 42-month-old. To test this possibility, participants were subdivided into three relatively equal-sized subgroups based on their age at the original infant acuity test (2-5 months, 6-15 months, and 16-42 months; n = 24, 28, and 24, respectively). Pearson and Spearman correlations were recalculated for each age group to compare measures from infancy (DQ, Z, TACI) to those from childhood (%fail, MONO, BINOC, WORST). Results showed that no apparent trends emerged from these analyses (range: p = .07 to .49). However, Figure 11 illustrates that for participants in the 16 to 42-month-old group, the relationship between acuity z-scores and the percentage of tests he

or she failed at follow-up during childhood approaches significance ($r = -.312$, $p = .07$). For reasons discussed above, it is reasonable to suggest that this relationship may have reached statistical significance had the sample size been larger (Mash & Dobson, 1998).

viii) Family income of participants. The correlational analyses showed that measures taken during infancy do not correlate with those taken during childhood, even when age/ developmental differences at the original testing were taken into consideration. To test for possible effects of family income, participants were grouped into one of three income categories: $39 000 or less, $40 000 to $59 000, or $60 000 or more per year (Canadian dollars). According to 1996 Newfoundland (Avalon Region) census data, the average family income for this area was $47 797/year, suggesting that the mean family income for this group was representative of the population in the study region (M = $40 000 to $59 000 category). Pearson and Spearman correlations were recalculated for each income subgroup, comparing infancy (DQ, Z, TACI) and childhood (%fail, MONO, BINOC, WORST) variables. Aside from one significant relationship (see Figure 12), the results showed a general lack of association between infant and childhood measures when participants were grouped according to level of family income (range: $p = .12$ to .50). Figure 12 shows that, for the subgroup with the highest family income ($60 000+/year), acuity z-scores during infancy are inversely related to the percentage of tests failed at follow up during childhood ($r = -.39$, $p < .05$). This suggests that higher acuity scores during infancy tended to be associated with lower test failure rates at

follow-up and lower infant acuity scores were associated with higher follow-up failure rates. This finding suggests that, compared to participants from the lower income groups, participants from the highest income families are more likely to have visual outcomes that are quantitatively consistent with their infancy assessments.

E. Specificity, Sensitivity, and Global Validity of the Teller Acuity Card Results During Infancy

Results from correlational analyses failed to uncover any significant associations between measures taken during infancy and those at follow-up. For this reason, we attempted a more clinically-oriented method for evaluating prediction, namely to determine the degree to which the category of a test result remains consistent over time. In other words, the degree to which a 'normal' result during infancy predicts a 'normal' result in childhood and an 'abnormal' result during infancy predicts an 'abnormal' result in childhood. In order to evaluate these categorical consistencies, and to determine how accurately and consistently the test could detect (or rule out) a disorder, we calculated the specificity, sensitivity, and global validity of the infant TAC test[3] (Kushner, Lucchese, & Morton, 1995).

i) Explanation of measures and analyses. In order to determine the specificity, sensitivity and global validity of the early TAC measure, participant's infant TAC result and his or her follow-up test results were first classified as either normal or abnormal,

based on norms used in standard Canadian paediatric ophthalmology practice. Because the infant TAC results are based on binocular acuity estimates, the calculations of sensitivity, specificity and global validity were made only for the binocular tests at follow-up (e.g., contrast sensitivity, binocular near and distance acuity, TAC, Ishihara colour plates, stereoacuity/stereopsis, broken wheel acuity, binocular alignment, and gross astigmatism). Specificity refers to the percentage of participants who have normal vision according to one of our tests at follow-up (e.g., binocular near acuity), and who also had normal results on the TAC test during infancy. Following Vital-Durand, Ayzac, and Pinzaru (1996), specificity was calculated by dividing the number of participants who had normal test results at both the original TAC session during infancy and the follow-up session during childhood (i.e., joint occurrence) by the number of participants who had normal test results at the follow-up session during childhood (irrespective of the result obtained during infancy). In contrast, sensitivity refers to the percentage of participants who show abnormal results on a follow-up test, and who also showed abnormal Teller grating acuity results during infancy. As such, the sensitivity of the test was calculated by dividing the number participants who had abnormal test results at both the original TAC session during infancy and the follow-up session during childhood by the number of participants with abnormal test results at the follow-up session during childhood (Vital-Durand et al., 1996). Thus, sensitivity and specificity values are analogous to the calculation of a conditional probability (i.e., the probability of obtaining

a specific follow-up result, given a specific original result). For the purposes of the current study, results of the specificity and sensitivity calculations were operationally defined as follows: 80-100% = "high" specificity/sensitivity, 60-79% = "moderate" specificity/sensitivity, and 59% or less = "low" specificity/sensitivity.

ii) Group results. Sensitivity and specificity scores were calculated for the at-risk group as a whole, and were also recalculated for the age subgroups (i.e., 2 to 5 months, 6 to 15 months, 16 to 42 months) described previously. These age-group calculations were included to evaluate whether or not the sensitivity and specificity of infant TAC results varied with age. As shown in the first column of results in Table 7 (all ages), the TAC was a highly specific test for the group as a whole (M = 0.84), with specificity ranging from 0.79 for the Ishihara colour plates, to 0.89 for binocular alignment. Surprisingly, however, data from the remainder of Table 7 show that as testing age increases, the specificity of the infant TAC result decreases. As shown in the second column of Table 7, normal TAC results were highly specific for the 2 to 5-month-olds (M = 0.95), but the means decrease to 0.89 and 0.69 for the 6 to 15-month-old and 16 to 42-month-old subgroups, respectively. Table 8 shows that, in comparison to the specificity results, TAC sensitivity values appear to be much lower (M all ages = 0.34), ranging from 0.20 for gross astigmatism to 0.47 for binocular alignment. Unfortunately, there were not enough data to calculate subgroup sensitivity scores for abnormal TAC tests.

In addition to specificity and sensitivity, the global validity of the TAC was also calculated. Global validity is analogous to determining the weighted mean for specificity and sensitivity and is calculated by adding the number of participants who had abnormal test results at both the infant and childhood sessions to the number of participants who had normal test results at both the infant and childhood sessions, and then dividing by the total number of cases where a participant contributed both an infant and a childhood test result. In this particular study, global validity determinations were highly influenced by the specificity data. Table 9 (column 1) shows that infant TAC results demonstrate high global validity for the at-risk group as a whole ($\underline{M}$ = 0.78; range: 0.74 to 0.85). Similar to the specificity data, Table 9 shows that global validity appears to vary with the age of the infant. For example, Table 9 shows that an early TAC result shows high global validity for the 2 to 5-month-olds ($\underline{M}$ = 0.84), but decreases to 0.83 and 0.68 at 6 for 15 months of age and 16 to 42 months of age, respectively.

F. Predictive Value of a TAC Measurement During Infancy

i) Explanation of measures and analyses. In addition to determining the specificity and sensitivity of an early TAC measure, we also assessed the ability of an early grating acuity estimate to predict long-term visual acuity outcome. Similar to Mash and Dobson (1998), predictive values were calculated for both normal and abnormal early TAC acuity results in order to determine the TAC's ability to accurately predict

(categorical) outcomes relative to normality. Recent studies by Saunders et al. (1996), Mash and Dobson (1998), and Dobson et al. (1999) evaluated the predictive value of an early TAC acuity estimate and collectively, these studies suggest that a normal grating acuity estimate during infancy tended to predict normal acuity outcome during childhood. However, except for an early measure of extreme visual impairment (i.e., apparent "blindness"), these studies show that an abnormal early TAC result is a poor predictor of later visual acuity. Similar to these previous studies, a goal of the current study was to evaluate the ability of the TAC to predict the results of a variety of tests of spatial and non-spatial vision.

For the calculation of predictive values, each participant's infant TAC result and his or her test results obtained during childhood were classified as either normal or abnormal. A normal test was defined as one in which the result fell within the normal or suspect range for that respective age group (refer to Appendix L for information regarding the classification of test results). An abnormal test was defined as one in which the result fell in the abnormal range for that respective age group. Following Mash and Dobson (1998), the predictive value for a normal test (i.e., the statistical counterpart of specificity) was calculated by dividing the number of participants who showed normal test results at both the infant and childhood sessions (i.e., joint occurrence) by the number of participants who showed normal TAC results during infancy (irrespective of the result obtained during childhood). Similarly, the predictive value for an abnormal test

(i.e., the statistical counterpart of sensitivity) was calculated by dividing the number of participants who showed abnormal test results at both the infant and childhood sessions by the number of participants who showed abnormal TAC results during infancy. Similar to sensitivity and specificity, predictive value is analogous to a conditional probability.

ii) Group results. Predictive values were calculated for the at-risk group as a whole, as well as for the three different age subgroups defined previously (i.e., 2 to 5 months, 6 to 15 months, and 16 to 42 months).The first column of Table 10 (all ages) shows that the predictive values for normal infant TAC tests were high (M = 0.91) and ranged from 0.87 to 0.98, with the lowest predictive values reported for contrast sensitivity and binocular alignment, and the highest value for the childhood TAC and Broken Wheel tests. Unlike the specificity calculations, the normal predictive values did not appear to vary significantly with age at original testing. That is, normal predictive values were uniformly high for all age subgroups (M = 0.89, 0.92, and 0.94 for the 2 to 5-month-olds, 6 to 15-month-olds, and 16 to 42-month-olds, respectively).

In contrast, Table 11 shows that the highest predictive value for an abnormal test (all ages) was 0.50 for binocular alignment, and for several outcome measures (e.g., TAC, binocular near acuity, colour vision) the predictive value was 0.00. These extremely low predictive values for the abnormal tests may explain, in part, the general lack of correlation found in the tests of association. Unfortunately, there were not enough data to calculate predictive values across age subgroups.

G. Comparison of Current Test Results with Ophthalmologists' Findings

To evaluate the concurrent validity of the measurements made by the experimenter at follow-up, the results from these tests were compared with those obtained from each participant's most recent eye exam conducted independently by a paediatric optometrist/ophthalmologist. To control for the influence of development, visual acuity results were compared only if they were obtained within 12 months of each other. A time frame of 3 years was used to compare the results of other tests (e.g., stereoacuity, strabismus, binocular alignment, eye movement disorders), as these functions tend to be less plastic during childhood. Overall, 92% (71 of 77 tests) of the current test results agreed with those obtained from the ophthalmologists. This high level of agreement suggests that the current test results did not over- or underestimate participants' visual capabilities and that the experimenter administered the tests competently. On the six occasions in which there was a significant difference between visual acuity estimations (defined conservatively as > ½ octave acuity difference), the differences were probably accounted for by a gradual worsening of myopia between the ophthalmologic exam and the current testing session (i.e., the child needed a new optical correction). Rapid progression of myopia is common in this age group, and the parents of all six participants were contacted by the study's supervisor. In each case, a follow-up examination by an eye care professional was recommended.

Discussion

The goal of the present study was to attempt to evaluate and describe the long-term visual development of a heterogeneous group of at-risk infants. All of these infants had experienced moderate to severe perinatal complications which jeopardized their long-term visual and neurological development. Traditionally, longitudinal studies of this nature have only followed children's visual development (namely, visual acuity) during the first 5 years of life. However, the present study extends beyond these age limits and evaluates children as old as 10 years of age. To the best of our knowledge, this is the most comprehensive study in this area to date, both in terms of the age range of the participants and in the number and variety of the spatial and non-spatial vision tests used.

Discussion of the results of this investigation will be organized around the questions posed in the introduction. More specifically, what is the long-term visual outcome of these at-risk infants, particularly in relation to their full-term peers? Secondly, what influence did individual perinatal risk factors have on their visual development? And finally, can a single measure of TAC grating acuity during infancy predict the visual outcome of at-risk infants?

Long-Term Visual Outcome of At-Risk Infants

Results from chi-square analyses show that the at-risk group differs from the control group on most measures of spatial vision, namely contrast sensitivity, monocular

near acuity, and monocular/binocular distance acuity. Similarly, the groups differ on many of the measures of non-spatial vision, namely stereoacuity, peripheral vision, and binocular alignment. More specifically, across the entire battery of tests, the at-risk children have a lower percentage of results within the normal range (M = 78% versus 93% for the full-term participants). Furthermore, the at-risk group shows a higher incidence of ocular disorders (e.g., strabismus, amblyopia) and refractive errors in comparison to the control participants.

Our results support the findings from several other follow-up investigations of at-risk infants during childhood and adolescence. For example, previous results have suggested that at-risk participants show some degree of visual acuity deficit and abnormal contrast sensitivity between 5 and 13 years of age (Dowdeswell et al., 1995; Gallo & Lennerstrand, 1991; McGinnity & Halliday, 1993; O'Connor et al., 1999; Powls et al., 1997). Similarly, at-risk children had poorer stereoacuity than control participants (Dowdeswell et al., 1995; Powls et al., 1997), as well as a higher incidence of colour vision deficits (Dowdeswell et al., 1995), ocular disorders (e.g., strabismus, nystagmus, eye movement disorders) (Gallo & Lennerstrand, 1991; McGinnity & Halliday, 1993; Powls et al., 1997), and refractive errors (Gallo & Lennerstrand, 1991). Together these findings suggest that at-risk infants have *some* permanent visual deficits and/or show a lag in visual development that persists well into the school-age and adolescent years.

It is noteworthy, however, that despite our finding that the at-risk group

performs more poorly than the control group for most tests, the majority of our at-risk participants are not severely impaired. In fact, most of their results appear to fall within the mid to lower end of the normal range. This pattern is consistent with results obtained in other studies of at-risk infants whose visual acuity was tested later at 2 to 42 months (Courage & Adams, 1997), 3 to 4 years (Getz, Dobson, & Luna, 1989; Sebris, Dobson, & Hartmann, 1984), 5.5 years (Dobson, et al., 1999), and at 10 to 18 years (Fledelius, 1981b). Overall, these findings suggest that although at-risk children are prone to visual deficiencies, they are not necessarily severely impaired. In fact, studies of LBW infants have shown that the majority of vision-related problems in the school-age and adolescent years can be categorized as minor acuity deficits, and/or relatively mild forms of strabismus (Alberman, Benson, & Evans, 1982; Fledelius, 1976, 1981b). Upon closer examination of the present study, the fact that any differences are found between the two groups at all may be attributable to the liberal nature of our chi-square calculations, in which abnormal and suspect results are often combined into one group.

Influence of Perinatal Risk Factors on Visual Outcome

Due to the fact that most individual risk factors occur with relatively low frequency in our participant group, formal statistical evaluation of their influence on visual development is impossible. However, non-statistical observations of the data *suggest* that bronchopulmonary dysplasia (BPD), seizures, pneumothorax and necrotizing enterocolitis (NEC) are associated with poorer visual outcome.

Unfortunately, most of the existing literature in this area is not *directly* comparable to the present research because previous findings are generally limited to preschool (or younger) children. Despite the difference between the age of the children, however, there are similarities between earlier findings and our own observations. For example, in a study of at-risk infants who experienced significant perinatal complications, Byars (1994) found that BPD and pneumothorax are associated with visual acuity deficits in children up to 36 months of age[4]. Similarly, Courage and Adams (1997) reported a relationship between BPD and decreased visual acuity in ELBW infants up to 42 months of age[4]. Furthermore, in a study of at-risk children up to 48 months of age, Harvey, Dobson, and Luna (1997) found that BPD correlated with poorer recognition acuity, as well as greater rates of strabismus and refractive errors. Overall, results from these younger children, combined with our own observations, suggest that infants who experience more serious respiratory complications (such as BPD), which often result in prolonged periods of mechanical ventilation, are more likely to have some type of lasting visual deficit and/or abnormality.

In sum, there is evidence to suggest that children who experience complications at or around the time of birth are at risk for abnormal visual development later in life. Unfortunately, there is no consistent evidence to indicate the *precise* influence of a *particular* risk factor on visual outcome. For this reason, more research is needed in order to determine the relationship between *individual* complications and later visual deficits. It

should be pointed out, however, that additional studies, larger sample sizes and extensive statistical analyses will not necessarily guarantee definitive results. As mentioned previously, determining the influence of a particular risk factor is difficult because children usually present with more than one, and certain risk factors naturally co-occur (e.g., prematurity and low birth weight; long periods of ventilation and respiratory distress syndrome). Future research in this area should attempt to investigate single, isolated risk factors or, more realistically, find ways to control for multiple risk factors. For example, researchers could investigate the differences between two at-risk groups that are matched according to a specific combination of risk factors (as few as possible), but that differ by only one (e.g., neonatal seizures). Presumably, any differences between the groups could be attributed to the specific risk factor in question. Alternatively, researchers could use large sample sizes and analyze/control for the influence of perinatal risk factors with multivariate statistics, thereby identifying 'clusters' of variables which seem most critical.

It is worth noting that research in other areas of childhood development (e.g., intelligence, behaviour disorders, mental health) has also been unsuccessful in determining the influence of early specific risk factors. As such, researchers have shifted their focus to the *cumulative effect* of early risk factors (Liaw & Brooks-Gunn, 1994; Sanson, Oberklaid, Pedlow, & Prior, 1991; Schorr, 1988; Werner & Smith, 1982). This model of development suggests that as the number of risk factors increases, so does the

incidence of adverse outcome. To date, support for this model has been found in the areas of intelligence and cognitive development (Liaw & Brooks-Gunn, 1994; Sameroff, Seifer, Baldwin, & Baldwin, 1993; Sameroff, Seifer, Baroces, Zax, & Greenspan, 1987) and, to some extent, in studies of behavioural maladjustment (Sanson et al., 1991). All would agree, however, that the absolute number of risk factors should not completely overshadow the synergy of the specific risk factors involved. Furthermore, unlike the present study, researchers in other areas have included risk factors from a wide variety of sources, including biological, within-child, familial, parental, environmental and socio-economic, in an attempt to fully represent the environment and conditions under which the child is developing.

Predictive Characteristics of a Single TAC Grating Acuity Estimate During Infancy

i) Comparison of TAC grating acuity estimates in infancy and childhood. In the current study, all 76 of the at-risk infants provided an estimate of TAC grating acuity during infancy and childhood. As infants, 18.4% of the participants (14 of 76) score in the abnormal acuity range, whereas only 1.3% of participants (1 of 76) show abnormal TAC results at follow-up. These results point to a vast improvement in visual acuity over time, however, there is a general lack of prediction of childhood grating acuity based on a single early measure of TAC grating acuity. In fact, due to the lack of variability in the childhood estimates, calculation of test-retest reliability was both inappropriate and impossible.

However, upon further examination of the data, it becomes evident that Teller Acuity Card results during childhood are not always in agreement with other measures of visual acuity and, in all such cases, the second TAC result appeared to be a gross over-estimate of spatial vision. In fact, the vast majority of the follow-up TAC scores were at or near ceiling level. Some research suggests that older children are able to detect an edge artifact on the test cards (i.e., the outline of the grating patch) and, when tested with a high spatial frequency grating, may rely on this cue to identify the location of an undetectable grating (see Moseley, Fielder, & Robinson, 1990; Robinson, Moseley, & Fielder, 1988). Despite instructions to identify only *visible* gratings in the current study, it is very likely that some children were responding to the edge artifact alone, thus artificially inflating their acuity estimates. Therefore, although the Teller Acuity Cards have been used with great success with infants and younger children, it is advisable that, for older children, researchers not use TAC as the *sole* estimator of visual acuity.

ii) Other correlational results. Aside from some expected results (e.g., positive relationship between birth weight and length of gestation), there were few significant correlations noted between perinatal, infancy and childhood results. Our findings did show that children with a greater number of risk factors tend to have lower acuity scores during infancy, and children with higher birth weights generally have better visual acuity outcomes in childhood. As a whole, these results suggest that healthier at-risk infants have a better prognosis for normal visual development in childhood.

The most important finding, however, resulted from comparison between estimates of infant Teller acuity and other measures. Grating acuity in infancy is not significantly related to any of the perinatal measures (e.g., birth weight, gestation, number of risk factors, NMI), nor did it correlate with DQ during infancy, the percentage of tests failed at follow-up, or later monocular and binocular acuity. It is worth noting, however, that a comparison between the 16 to 42-month-olds' acuity z-scores and percentage of tests failed at follow-up does approach significance. This suggests that TAC acuity estimates after the first year of age may be more predictive of later outcome, although further testing with a larger sample size would be necessary to draw more firm conclusions. Furthermore, analyses of income suggest that among those with the highest family income (> $60,000/year), a significant negative relationship exists between acuity during infancy and the percentage of tests failed at follow-up. Unfortunately, it is difficult to interpret this result because little research has been conducted regarding the influence of socioeconomic status on visual outcome (see Courage et al., 1998; Nelson, Innes, Rioux, & Wasten, 1995). Except for the children in the highest income bracket, there appears to be little consistency between early and later measures. Overall, despite controlling for the influence of extreme cases, age of participants, and family income, there is no **quantitative** evidence to suggest that a single estimate of Teller grating acuity in infancy can adequately predict visual outcome in childhood. Upon closer examination of the data, however, it is also possible that the restricted range of infancy and follow-up

scores may mask or misrepresent the predictive power of the TAC (Mash & Dobson, 1998; Dobson et al., 1999). Therefore, further exploration of the predictive utility of the TAC is warranted.

iii) Predictive value, specificity, sensitivity, and global validity of TAC grating acuity estimations during infancy. From a clinical standpoint, the ability of a test score to predict "normal" and "abnormal" outcome is very important. According to our correlational results, early Teller Acuity Card estimates are very poor predictors of later visual outcome. It is worth noting, however, that the use of correlational analyses has long been criticized for having low predictive ability (see Bland & Altman, 1986). For this reason, researchers have augmented their studies with estimates of *predictive value*. Predictive values allow a researcher to define "normal" and "abnormal" cases based on a qualitative versus a quantitative assessment. More importantly, predictive values are used to make predictions about *individual* participants, thus increasing the utility of this type of assessment in clinical investigations.

In the current study, we evaluated the predictive value of an early TAC test, as well as its sensitivity, specificity and global validity. Both specificity and its statistical counterpart, the predictive value of a normal TAC score during infancy, are high (all ages: M = .84 and .91, respectively), as were measures of global validity (all ages: M = .78). However, measures of sensitivity and its statistical counterpart, the predictive value of an abnormal TAC score during infancy, are *substantially* lower (all ages: M = .34 and .18,

respectively). Together, these results suggest that an early *normal* result is a better qualitative predictor of future outcome than is an *abnormal* result. More specifically, these results imply that an infant categorized as 'visually normal' will *tend* to have normal results on subsequent follow-up tests of both spatial and non-spatial vision. In contrast, the visual development of a 'visually abnormal' infant is less clear and consistent, therefore no judgement about his/her outcome can be made with certainty. Similarly, our results show that the TAC is a highly specific screening tool for identifying those children who were categorized as "normal" according to our follow-up tests, but it is *considerably* less sensitive for identifying those participants with abnormal results. However, it is important to note that, similar to the general population, a *much* greater proportion of normal versus abnormal results were found at both testing ages. By definition, this *dramatically increases* the probability of finding high normal predictive value and specificity. Therefore, from a clinical perspective, the significance of these results may be **overestimated** and outcome predictions based on these findings (i.e., "normal" results) must be made with caution.

Nonetheless, our findings are consistent with those reported in other similar studies. Mash and Dobson (1998) compared TAC results obtained during infancy to TAC and HOTV results from the same children at 4 years. In a more recent study, Dobson et al. (1999) followed-up preterm children at 5.5 years of age and compared TAC results obtained during infancy to TAC and Snellen acuity scores obtained in childhood. Both

studies found high normal predictive values (.76 and .94, respectively, for TAC2; .91 for HOTV, and .87 for Snellen) , but *considerably* lower abnormal predictive values [.58 (M) and . 89, respectively, for TAC2; .68 for HOTV; Snellen was not calculated]. Similarly, in a FPL study of full-term children, Saunders et al. (1996) found that the majority of children who had normal grating acuity in the first year of life tended to maintain that status, whereas the visual outcome of infants who demonstrated abnormal grating acuity was more unpredictable. The one notable exception to this overall pattern of results is that, not surprisingly, children with no measurable acuity during infancy tended to remain severely impaired or blind into the early school-age years (Dobson et al., 1999). In sum, all studies (including the current research) show consistently higher normal predictive values and lower abnormal predictive values. However, low abnormal predictive values may be attributable to the small number of children who provided an abnormal TAC result during infancy, and/or the lack of variability in the infancy scores. Finally, it is worth noting that all these conclusions are restricted to the development of spatial vision. As the present study is the first to consider the development of non-spatial vision, we have no means of comparing our data to those of others.

Limitations of Current Study and Directions for Future Research

Although the current study has overcome some common shortcomings of past research, and has expanded upon the current literature in many ways, it is not without its own limitations. First, the perinatal and infant information were obtained

retrospectively, and were based on data collected from a variety of sources. For example, medical information was recorded by personnel from several health care centres in Newfoundland and Labrador, as well as by staff of the Provincial Perinatal Programme, whereas TAC and DQ results were recorded by several trained observers. Overall, our initial data set was compiled over a 10 year period, and information was often transferred from one chart or data sheet to another. As such, we cannot assume that the accuracy and precision exercised in data collection and transfer was consistent. Second, the original TAC grating acuity estimates were assessed under binocular viewing conditions only . Unfortunately, under these testing conditions, a monocular visual deficit or disease would have gone undetected. Furthermore, *direct* comparisons between early TAC results and follow-up results were thus restricted to binocular data. Therefore, whenever possible and appropriate, *all* future tests of visual functioning should include both binocular and monocular assessments.

Other suggestions for improvement can also be offered. First, infants should be tested more than once, over a short period of time, to help reduce variability in their test scores. Second, although our subject group was representative of the at-risk infant population in *this geographical area* and we did not selectively exclude any children, there were very few children with serious complications and impairments. It should be noted, however, that there is only *one* children's hospital in the province of Newfoundland and Labrador, and our high discharge rate is directly related to the fact that many of the

severely ill infants die during transfer. As such, future research should be conducted in a centre with a greater number of high-risk infants. Third, future studies might also include additional early measures of visual functioning (e.g., contrast sensitivity, stereoacuity), as well as early and follow-up measures of cognitive functioning (including data about parental educational level) and motor development. By including this additional information, researchers will be better able to evaluate whether, as suggested by some (Courage & Adams, 1997), early vision estimates are good predictors of general neurological functioning.

Conclusions

In conclusion, the results reported here, taken with other research, indicate that infants who experience significant perinatal complications are at a *greater* risk for developing a variety of long-term visual deficits than are their healthy, full-term peers. It is worth noting, however, that the extent of the vision problems within this population can vary, with only a *minority* of the at-risk infants being profoundly afflicted. In fact, despite falling below their corrected age norms, most infants do score within the mid to lower end of the "clinically normal" range. Unfortunately, our observations failed to uncover any evidence to suggest that visual irregularities are *definitively* related to any single perinatal risk factor. Finally, the most important conclusion to be drawn from this research is that, overall, an early Teller Acuity Card estimate is a *poor* predictor of long-term visual outcome in children with perinatal complications. As such, any predictions

based upon a single early TAC estimate **must** be made and interpreted with caution, even when the initial result is normal. This recommendation is particularly crucial in light of the commercial success and the widespread use of this particular acuity test throughout the world.

Footnotes

[1] Children in the original test group were between 2 and 42 months of age (see Adams, Courage, Byars, & McKim, 1994). However, for the purposes of this paper, these children will hereafter be collectively referred to as "infants" and/or this testing phase will be referred to as the "original", "initial", or "infancy" testing phase.

[2] The Neonatal Medical Index (NMI) is designed to describe the broad medical course of preterm infants during their initial hospitalization. As such, it is not an exhaustive list of all of the complications and illnesses that the infant has experienced during the neonatal period. An infant is assigned a classification from 1 (no serious complications) to 5 (most serious complications), based primarily on his/her birth weight and the need for assisted ventilation. Other classification criteria include: use of medications such as theophylline and indomethacin; major surgery; meningitis; PVH-IVH; seizures; PVL (see Korner et al., 1993 for a complete description).

[3] Estimates of a test's sensitivity and specificity are the traditional statistics used to report its diagnostic accuracy in the psychometric and clinical literatures (see Wissow, 1997). Specifically, the sensitivity and specificity of a test (e.g., Teller Acuity Cards) refer to its success in identifying individuals who have or do not have, respectively, a particular disease or condition (e.g., subnormal visual acuity). However, a test's positive and negative predictive values provide estimates of the likelihood that a positive result means that a particular condition will be present (i.e., positive or abnormal predictive value) and that a negative result means that the condition will be absent (i.e., negative or normal predictive value). These two sets of test characteristics are related in that both provide information on how well a normal (negative predictive value; specificity) estimate or an abnormal (positive predictive value; sensitivity) estimate of performance predicts ultimate functioning. They differ in that specificity/sensitivity are test *accuracy* statistics, whereas predictive values provide estimates of the *confidence* that a user can have in the expected outcome.

[4] Similar to this thesis, children in the Byars (1994) and Courage and Adams (1997) studies were selected from the larger subject group described in Adams, Courage, Byars, & McKim (1994).

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Table 1

Test Battery Completion Rates for At-Risk Participants as a Function of Age

Age (years)	Number of participants	Mean # of tests completed (SD)[a]	Mean % of tests completed (SD)
2-3	10	6.3 (2.8)	37.0 (16.5)
4	12	11.5 (3.0)	68.1 (17.4)
5	11	13.6 (3.6)	80.7 (21.5)
6	6	13.5 (4.7)	80.3 (28.6)
7	17	16.3 (1.6)	95.8 (9.5)
8	10	15.0 (4.3)	88.9 (25.3)
9-10	10	16.7 (0.7)	98.2 (4.1)

Note. [a] 17 tests in the battery.

Table 2

Summary of Chi-square Analyses[a] Comparing the At-Risk and Control Groups' Performance on Each of the Vision Tests Within the Battery

Test	df	n	χ^2
Spatial Vision Tests:			
Contrast Sensitivity (binocular)	1	55	33.28*
Near Acuity (binocular)[b]	2	64	2.65
Near Acuity (monocular)[b]	1	116	630.44*
Distance Acuity (binocular)[c]	1	61	29.33*
Distance Acuity (monocular)[c]	1	92	41.99*
Teller Grating Acuity (binocular)	1	76	1.01
Broken Wheel (Landolt) Acuity (binocular)	1	62	0.06
Stereo Acuity / Stereopsis	1	65	51.59*
Peripheral Vision (monocular)	1	92	138.26*
Ishihara Colour Plates	1	65	0.25
Astigmatism (binocular)	1	64	4.65
Binocular Alignment	1	76	31.93*

Note. [a]Due to the multiple comparisons (n =12), the alpha level was adjusted, by the Bonferroni method, to .004. [b]HOTV (older Ss) and Tumbling E (younger Ss) combined for the analysis. [c]Snellen (older Ss) and Tumbling E (younger Ss) combined for the analysis.
*$p < .001$.

Table 3

Percentage of Test Score Classifications for Each Vision Test: At-Risk Versus Control Group

Test	Group	Normal (%)	Suspect (%)	Abnormal (%)	No data (x/n)
Contrast Sensitivity*	At-Risk[a]	76.4	7.3	16.4	21/76
	Control[b]	90.6	5.7	3.7	8/61
Near Acuity (binocular)	At-Risk	89.1	4.7	6.3	12/76
	Control	100.0	0.0	0.0	1/61
Near Acuity* (left eye)	At-Risk	75.9	13.8	10.3	18/76
	Control	98.3	1.7	0.0	2/61
Near Acuity* (right eye)	At-Risk	79.3	10.3	10.3	18/76
	Control	100.0	0.0	0.0	2/61
Distance Acuity* (binocular)	At-Risk	60.7	23.0	16.4	15/76
	Control	84.5	13.8	1.7	3/61
Distance Acuity* (left eye)	At-Risk	26.1	37.0	37.0	30/76
	Control	63.1	32.6	4.3	15/61

(table continues)

Test	Group	Normal (%)	Suspect (%)	Abnormal (%)	No data (x/n)
Distance Acuity* (right eye)	At-Risk	34.8	34.8	30.4	30/76
	Control	63.1	32.6	4.3	15/61
TAC	At-Risk	97.4	1.3	1.3	0/76
	Control	98.4	0.0	1.6	0/61
Broken Wheel Test	At-Risk[c]	96.8	N/A	3.2	9/71
	Control	100.0	N/A	0.0	3/61
Ishihara Colour Plates	At-Risk	93.8	N/A	6.2	11/76
	Control	100.0	N/A	0.0	5/61
Stereo Acuity*	At-Risk	81.5	6.2	12.3	11/76
	Control	96.6	1.7	1.7	3/61
Peripheral Vision (left eye)*	At-Risk	69.6	23.9	6.5	30/76
	Control	94.9	2.6	2.6	22/61
Peripheral Vision (right eye)*	At-Risk	71.7	10.9	17.4	30/76
	Control	97.4	0.0	2.6	22/61

(table continues)

Test	Group	Normal (%)	Suspect (%)	Abnormal (%)	No data (x/n)
Corneal Reflection*	At-Risk	86.8	N/A	13.2	0/76
	Control	95.1	N/A	4.9	0/61
Convergence*	At-Risk	90.9	N/A	9.1	10/76
	Control	100.0	N/A	0.0	1/61
Tracking[d]	At-Risk	97.2	N/A	2.8	4/76
	Control	98.3	N/A	1.7	2/61
Astigmatism	At-Risk	92.2	N/A	7.8	12/76
	Control	96.7	N/A	3.3	1/61

Note. N/A = classification not applicable/appropriate for test.
[a] At-risk sample, n = 76. [b] Control sample, n = 61. [c] Test was not available for first 5 at-risk participants, therefore n = 71. [d] Corneal reflection and convergence were responsible for the significant chi-square value relating to binocular alignment.
* significant difference found between at-risk and control groups (chi-square analyses; all $p < .001$).

Table 4

Comparison of Mean Test Failure Rates and Visual Acuity Outcomes: Entire At-Risk Group Versus Risk Factor Subgroups

Risk factor subgroup	n[a]	M % tests failed	M monocular outcome[b]	M binocular outcome[b]
Neurological signs	16	19.8	S	–
Seizures	6	30.7*	S	S+
LHC	15	21.6	S	S+
Hypoglycaemia	6	13.5	S+	–
Metabolic acidosis	13	9.9	S+	N
RDS	30	22.9	S	S+
BPD	5	28.0*	S–	S*
PDA	9	26.4	S	S+
Apnea	17	21.6	S	S+
Asphyxia	20	13.8	S+	N
Pneumothorax	5	35.4*	S–	S+
NEC	5	41.6*	A*	S–*
All at-risk participants	**76**	**18.5**	S	S+

Note. [a] only risk factors that were experienced by a minimum of five participants were evaluated. [b] see the notes at the end of Appendix A for an explanation of how the means were calculated. * a mean difference of 10% or more between the entire at-risk group's failure rate and a risk factor subgroup's failure rate was defined as notable or a mean difference of two or more categories between the entire at-risk group's monocular or binocular acuity outcome and a risk factor subgroup's monocular or binocular acuity outcome was defined as notable (see the notes at the end of Appendix A for an explanation of the categories).

Table 5

Pearson Correlations Between Perinatal, Infancy and Follow-Up Childhood Data for At-Risk Participants

		Perinatal factors			Infancy measures		Childhood measures
		BW	GEST	RF	DQ	Z	% fail
Perinatal factors	BW	--	.889***	-.564***	.316**	.091	-.069
	GEST		--	-.685***	.388***	.150	-.043
	RF			--	-.315**	-.190*	.169
Infancy measures	DQ				--	.174	-.042
	Z					--	-.167
Childhood measures	% fail						--

Note. **BW** = birth weight (grams); **GEST** = gestation (weeks); **RF** = number of risk factors experienced at or around birth (range: 1-11); **DQ** = developmental quotient (as assessed by Griffith's Scales of Infant Development); **Z** = z-score based on original TAC acuity estimate (range from worst to best: -4.4 to 2.7); **% fail** = percentage of tests failed at follow-up during childhood (range: 0-60).
***$p < .0005$. **$p < .005$. *$p = .05$.

Table 6

Spearman Correlations Between Perinatal, Infancy and Follow-Up Childhood Data for At-Risk Participants

		Perinatal factors				Infancy measure	Childhood measures		
		BWCAT	GESTCAT	RFCAT	NMI	TAC1	MONO	BINOC	WORST
Perinatal factors	BWCAT	--	.884***	-.484***	-.154	-.067	.232*	.212*	.210*
	GESTCAT		--	-.562***	-.307**	-.060	.080	.134	.128
	RFCAT			--	.596***	.056	.070	-.086	-.009
	NMI				--	.021	.020	-.108	-.035
Infancy measure	TAC1					--	-.034	-.052	-.078

(table continues)

		Perinatal factors				Infancy measure	Childhood measures		
		BWCAT	GESTCAT	RFCAT	NMI	TACI	MONO	BINOC	WORST
Childhood measures	MONO						--	.562***	.969***
	BINOC							--	.657***
	WORST								--

Note. Refer to text for detailed information regarding the data headings. **BWCAT** = birth weight categories (range from lowest to highest: 1-7); **GESTCAT** = gestation categories (range from shortest to longest: 1-5); **RFCAT** = perinatal risk factor categories (range from lowest to highest: 1-4); **NMI** = perinatal Neonatal Medical Index categories (range from best to worst: 1-5); **TACI** = categories based on original TAC acuity estimate (range from best to worst: 1-6); **MONO** = categories based on overall monocular acuity estimate at follow-up (range from worst to best: 1-3); **BINOC** = categories based on overall binocular acuity estimate at follow-up (range from worst to best: 1-3); **WORST** = categories based on overall worst case acuity estimate at follow-up (range from worst to best: 1-3).
*** $p < .0005$, ** $p < .005$. * $p \leq .05$.

Table 7

Specificity of TAC Results During Infancy Compared with Results of All Binocular Tests at Follow-Up During Childhood

Test	Specificity score (n[a])			
	All ages	2-5 months	6-15 months	16-42 months
Contrast Sensitivity	0.87 (46)	1.00 (10)	0.89 (19)	0.76 (17)
Near Acuity (binocular)	0.80 (60)	0.93 (14)	0.91 (23)	0.61 (23)
Distance Acuity (binocular)	0.86 (51)	0.92 (13)	0.90 (21)	0.76 (17)
TAC 2	0.81 (75)	0.96 (23)	0.86 (28)	0.63 (24)
Broken Wheel	0.87 (60)	0.94 (17)	0.96 (23)	0.70 (20)
Ishihara Plates	0.79 (61)	0.94 (17)	0.86 (21)	0.61 (23)
Stereoacuity	0.82 (57)	0.93 (14)	0.88 (24)	0.68 (19)
Binocular Alignment	0.89 (61)	0.95 (19)	0.88 (25)	0.82 (17)
Astigmatism	0.81 (59)	0.94 (18)	0.86 (22)	0.63 (19)
Mean	0.84	0.95	0.89	0.69

Note. [a] bracketed value shows the number of cases that the specificity score is based upon: n = number of tests showing normal results at the follow-up session during childhood.

Table 8

Sensitivity of TAC Results During Infancy Compared with Results of All Binocular Tests at Follow-Up During Childhood

Test	Sensitivity score (n^{ab})			
	All ages	2-5 months	6-15 months	16-42 months
Contrast Sensitivity	0.40 (10)	-----	-----	-----
Near Acuity (binocular)	-----	-----	-----	-----
Distance Acuity (binocular)	0.40 (10)	-----	-----	0.80 (5)
TAC 2	-----	-----	-----	-----
Broken Wheel	-----	-----	-----	-----
Ishihara Plates	-----	-----	-----	-----
Stereoacuity	0.25 (8)	-----	-----	-----
Binocular Alignment	0.47 (15)	0.00 (5)	-----	0.86 (7)
Astigmatism	0.20 (5)	-----	-----	-----
Mean	0.34	0.00	-----	0.83

Note. [a] bracketed value shows the number of cases that the sensitivity score is based upon: n = number of tests showing abnormal results at the follow-up test during childhood. [b] predictive values were calculated only for those tests in which at least five participants showed abnormal results.

Table 9

Global Validity of the TAC Results During Infancy Compared with Results of All Binocular Tests at Follow-Up During Childhood

Test	Global validity (n[a])			
	All ages	2-5 months	6-15 months	16-42 months
Contrast Sensitivity	0.79 (56)	0.77 (13)	0.77 (22)	0.81 (21)
Near Acuity (binocular)	0.75 (64)	0.81 (16)	0.88 (24)	0.58 (24)
Distance Acuity (binocular)	0.79 (61)	0.86 (14)	0.76 (25)	0.77 (22)
Broken Wheel	0.85 (62)	0.89 (18)	0.96 (23)	0.71 (21)
TAC 2	0.80 (76)	0.92 (24)	0.86 (28)	0.63 (24)
Ishihara Plates	0.74 (65)	0.89 (18)	0.78 (23)	0.58 (24)
Stereoacuity	0.75 (65)	0.77 (17)	0.84 (25)	0.65 (23)
Binocular Alignment	0.80 (76)	0.75 (24)	0.82 (28)	0.83 (24)
Astigmatism	0.77 (64)	0.94 (18)	0.79 (24)	0.59 (22)
Mean	0.78	0.84	0.83	0.68

Note. [a] bracketed value shows the number of cases that the global validity calculation is based upon: n = total number of cases where participant completed both the TACI and follow-up tests.

Table 10

Predictive Values of Normal TAC Tests During Infancy For All Binocular Measures During Childhood

Test	Predictive value (n[a])			
	All ages	2-5 months	6-15 months	16-42 months
Contrast Sensitivity	0.87 (46)	0.77 (13)	0.85 (20)	1.00 (13)
Near Acuity (binocular)	0.92 (52)	0.87 (15)	0.95 (22)	0.93 (15)
Distance Acuity (binocular)	0.88 (50)	0.92 (13)	0.83 (23)	0.93 (14)
TAC 2	0.98 (62)	0.96 (23)	1.00 (24)	1.00 (15)
Broken Wheel	0.98 (53)	0.94 (17)	1.00 (22)	1.00 (14)
Ishihara Plates	0.92 (52)	0.94 (17)	0.90 (20)	0.93 (15)
Stereoacuity	0.89 (53)	0.81 (16)	0.95 (22)	0.87 (15)
Binocular Alignment	0.87 (62)	0.78 (23)	0.92 (24)	0.93 (15)
Astigmatism	0.92 (52)	1.00 (17)	0.90 (21)	0.86 (14)
Mean	0.91	0.89	0.92	0.94

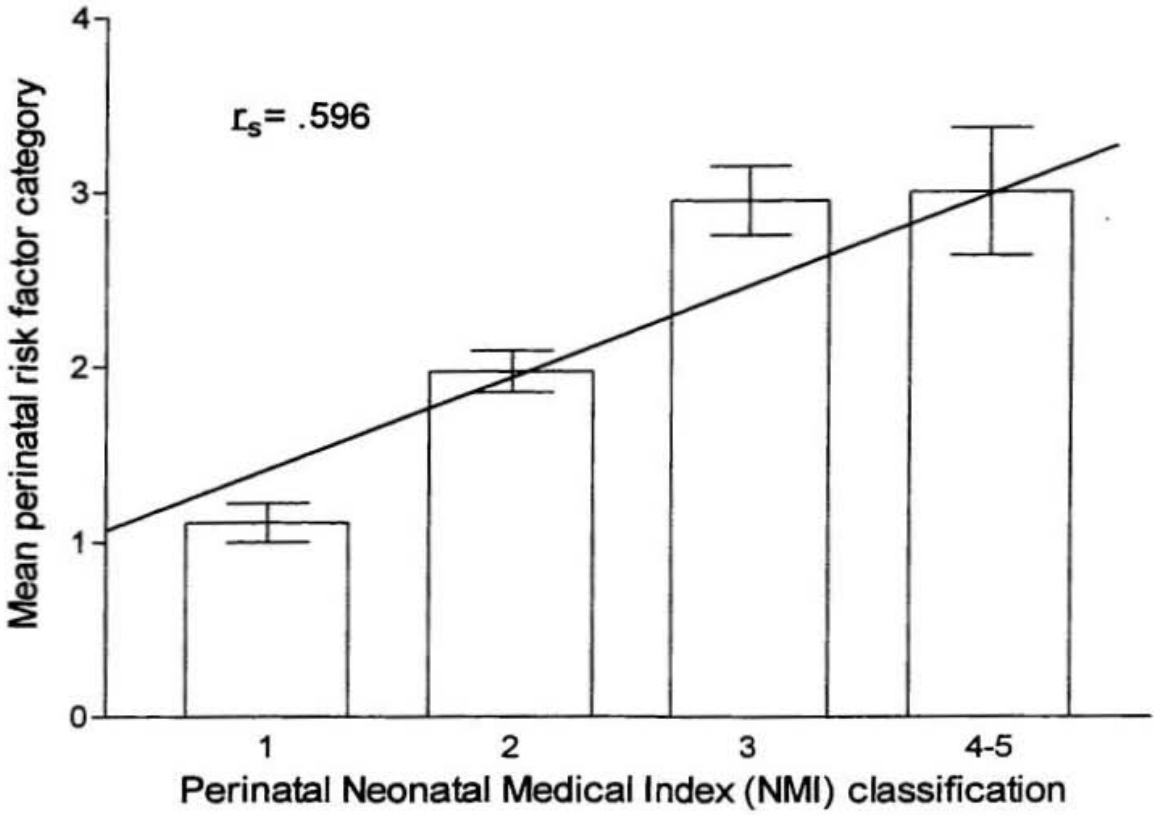
Note. [a] bracketed value shows the number of cases that the predictive value is based upon: n = number of tests showing normal results at the original TAC test during infancy.

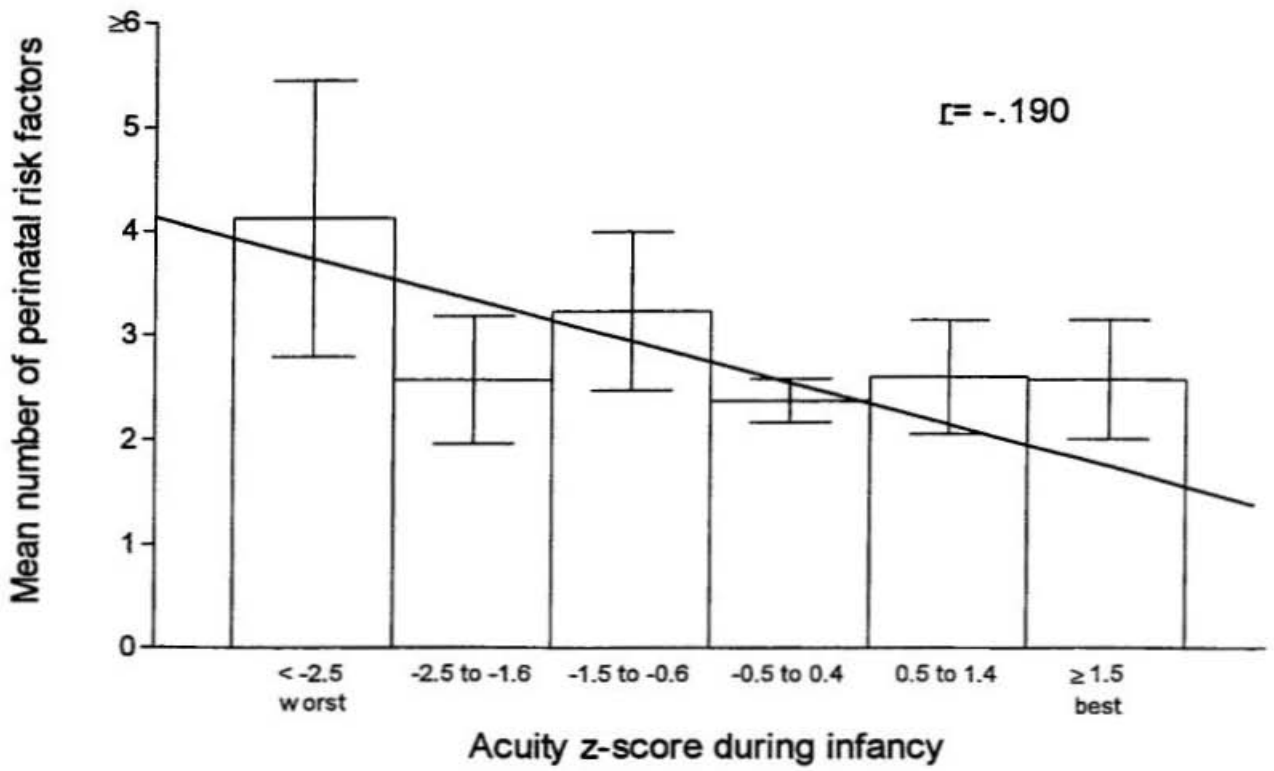
Table 11

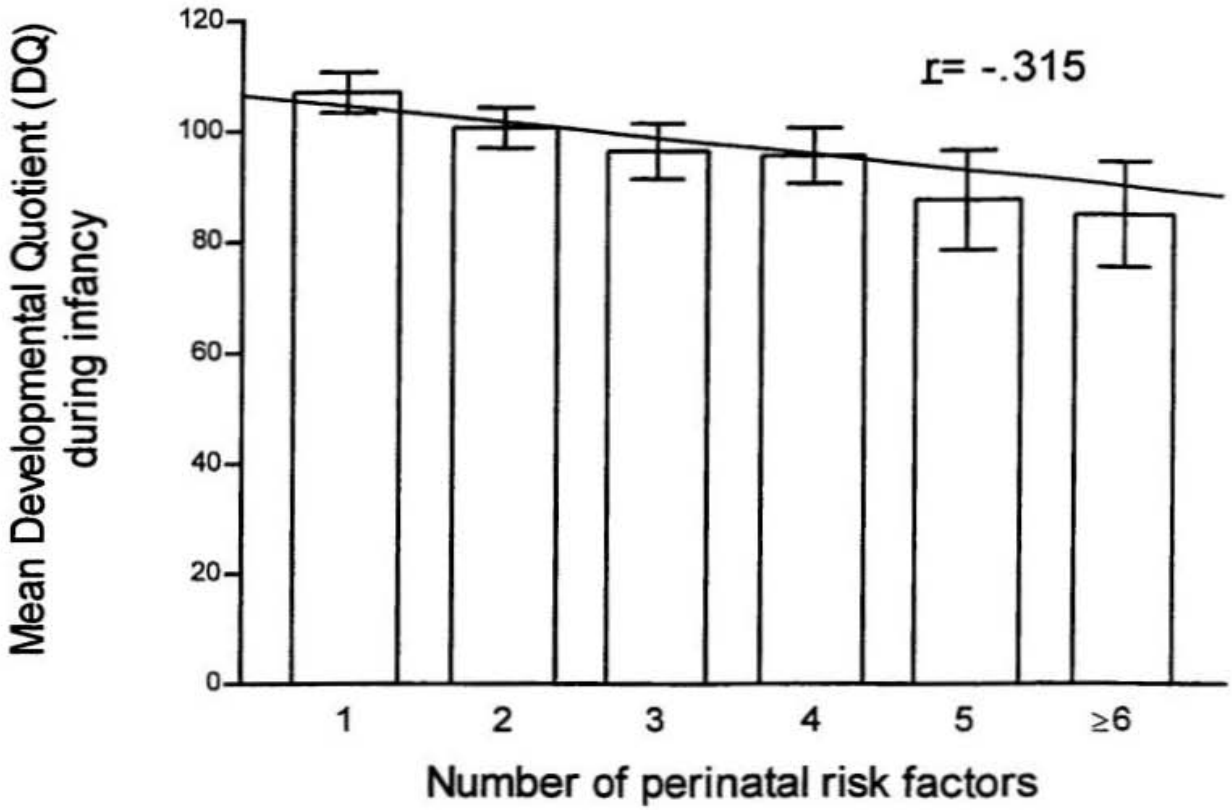
Predictive Values of Abnormal TAC Tests During Infancy For All Binocular Measures During Childhood

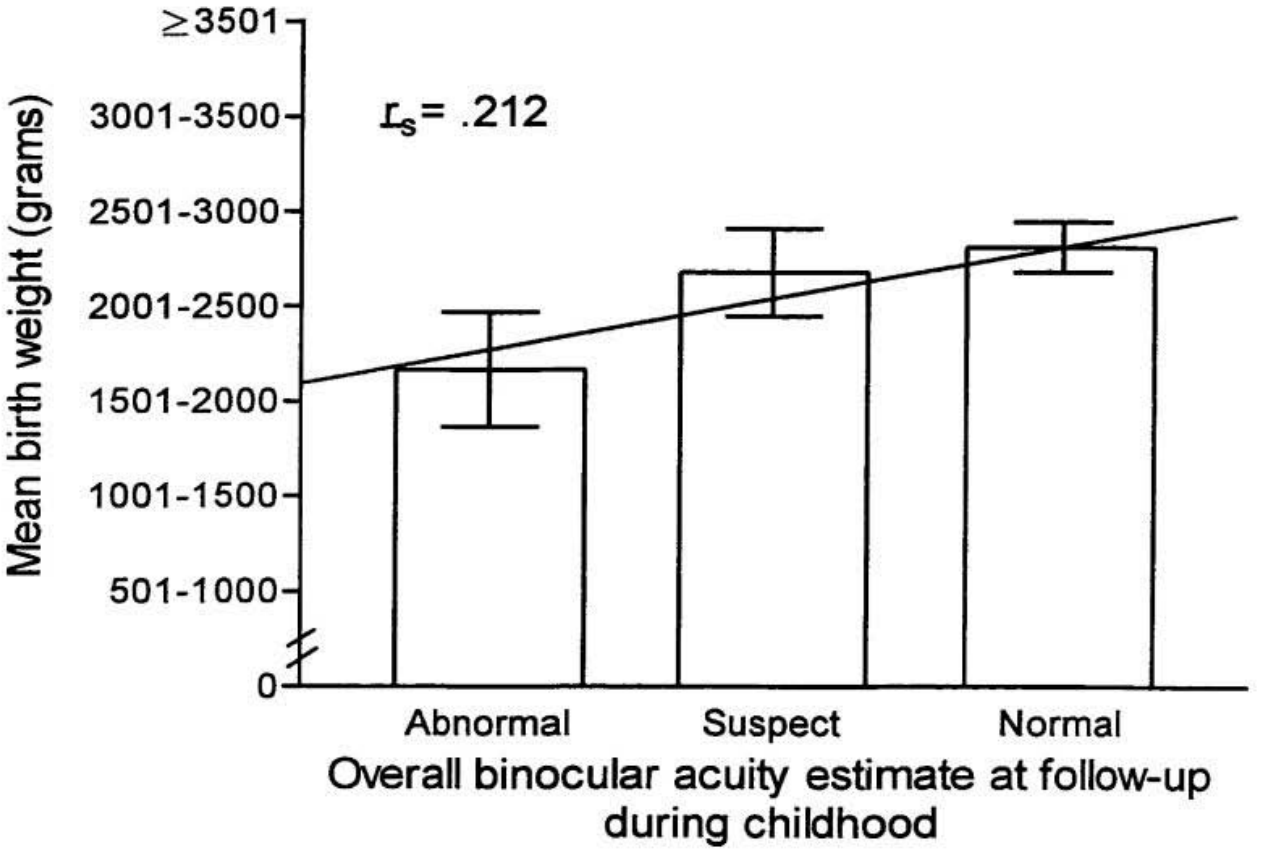
Test	Predictive value (n^{ab})			
	All ages	2-5 months	6-15 months	16-42 months
Contrast Sensitivity	0.40 (10)	---	---	0.50 (8)
Near Acuity (binocular)	0.00 (12)	---	---	0.00 (9)
Distance Acuity (binocular)	0.36 (11)	---	---	0.50 (8)
TAC 2	0.00 (14)	---	---	0.00 (9)
Broken Wheel	0.11 (9)	---	---	0.14 (7)
Ishihara Plates	0.00 (13)	---	---	0.00 (9)
Stereoacuity	0.17 (12)	---	---	0.25 (8)
Binocular Alignment	0.50 (14)	---	---	0.67 (9)
Astigmatism	0.08 (12)	---	---	0.13 (8)
Mean	0.18	---	---	0.24

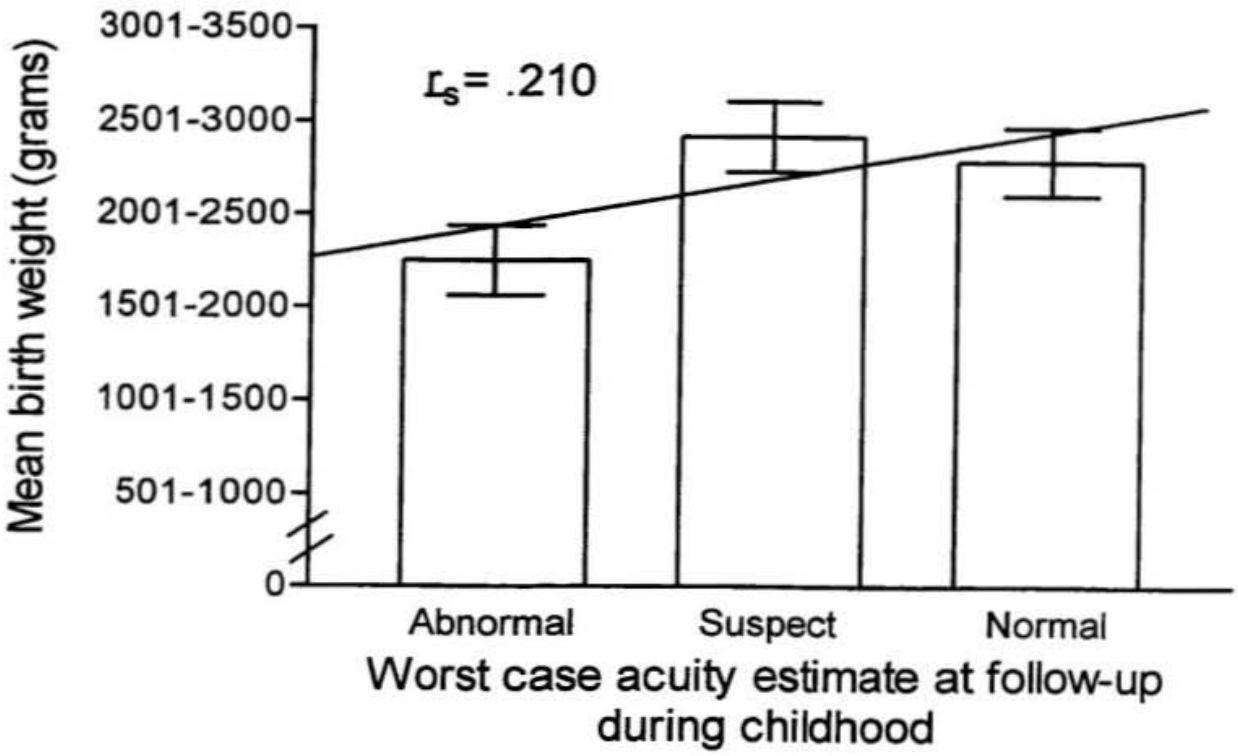
Note. [a] bracketed value shows the number of cases that predictive value is based upon: n = number of tests showing abnormal results on original TAC test during infancy. [b] predictive values were calculated only for those tests in which at least five participants showed abnormal results.

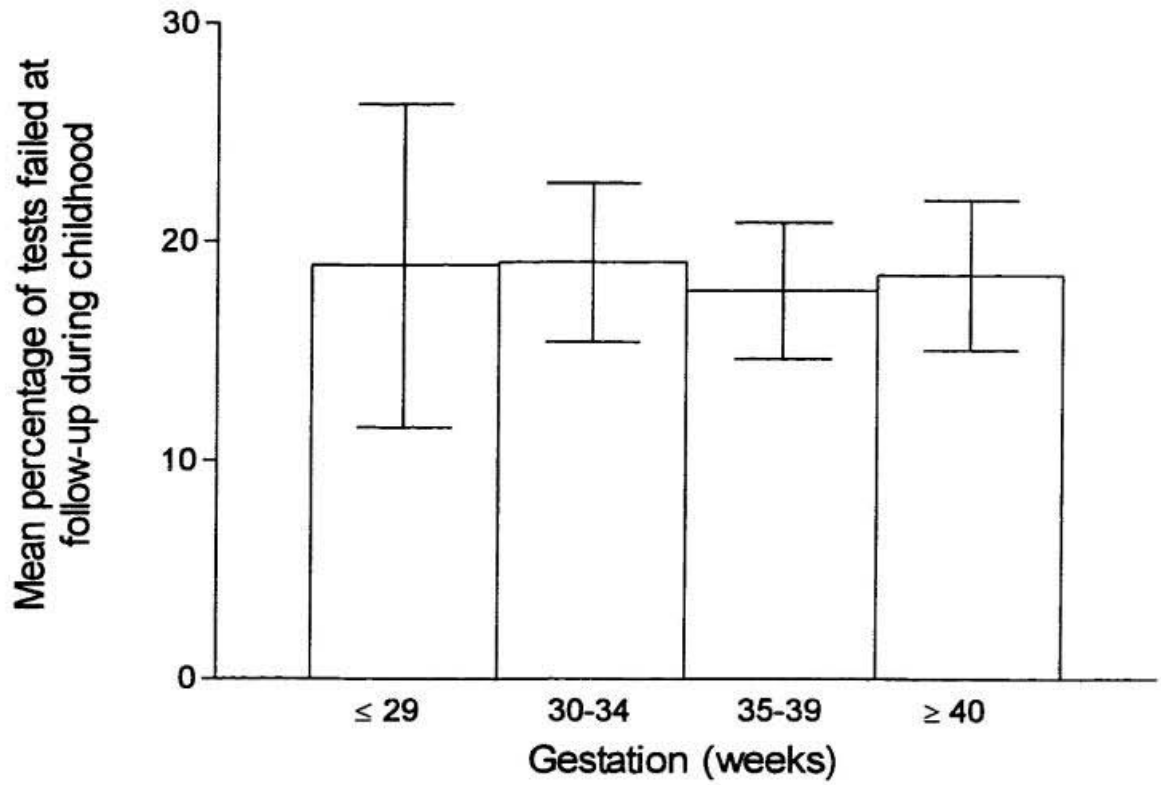

r_s= .596
Mean perinatal risk factor category
0
1
2
3
4
1
2
3
4-5
Perinatal Neonatal Medical Index (NMI) classification

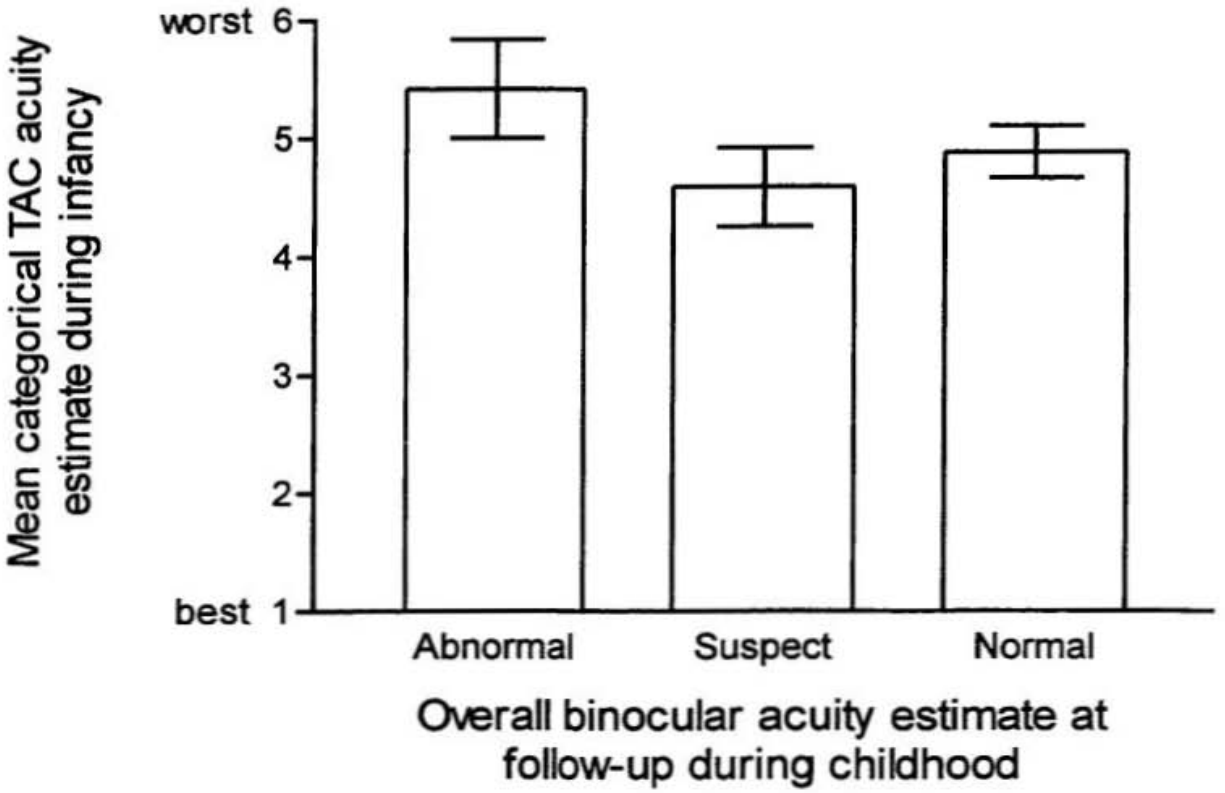

Mean number of perinatal risk factors
≥6
5
4
3
2
1
0
r= -.190
< -2.5 worst
-2.5 to -1.6
-1.5 to -0.6
-0.5 to 0.4
0.5 to 1.4
≥ 1.5 best
Acuity z-score during infancy

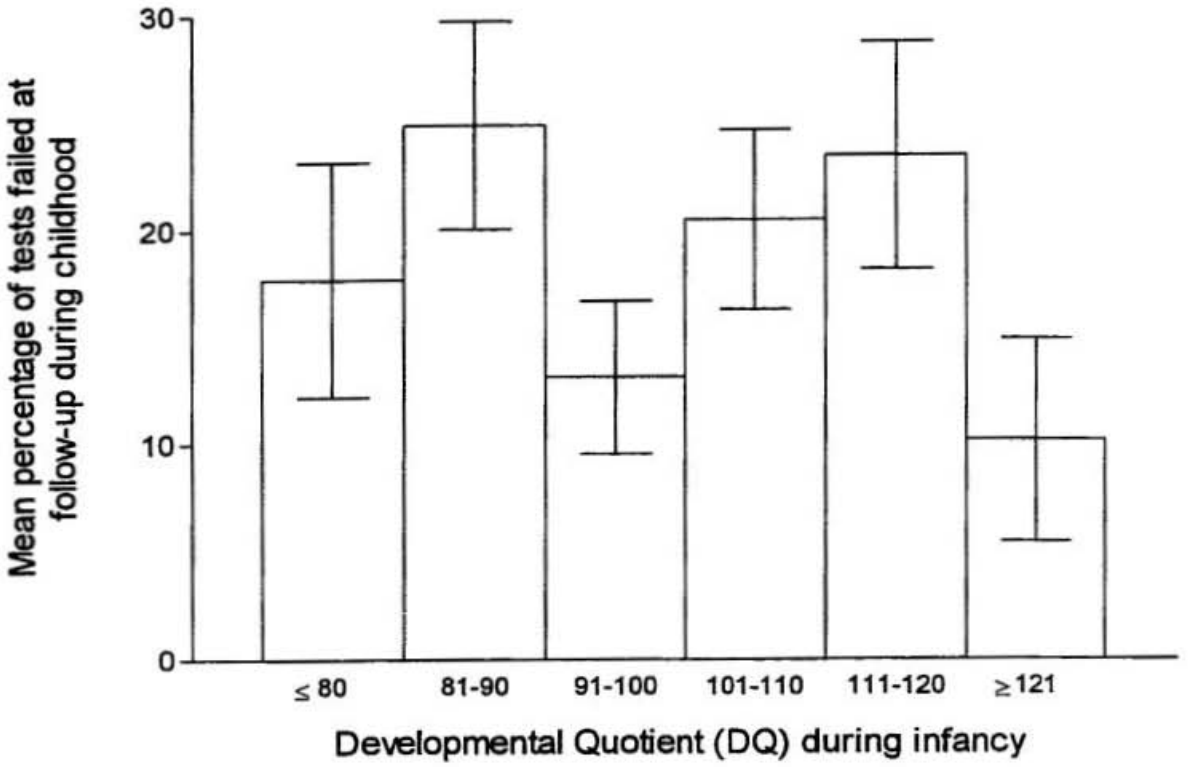

Mean Developmental Quotient (DQ) during infancy
120
100
80
60
40
20
0
r= -.315
1
2
3
4
5
≥6
Number of perinatal risk factors

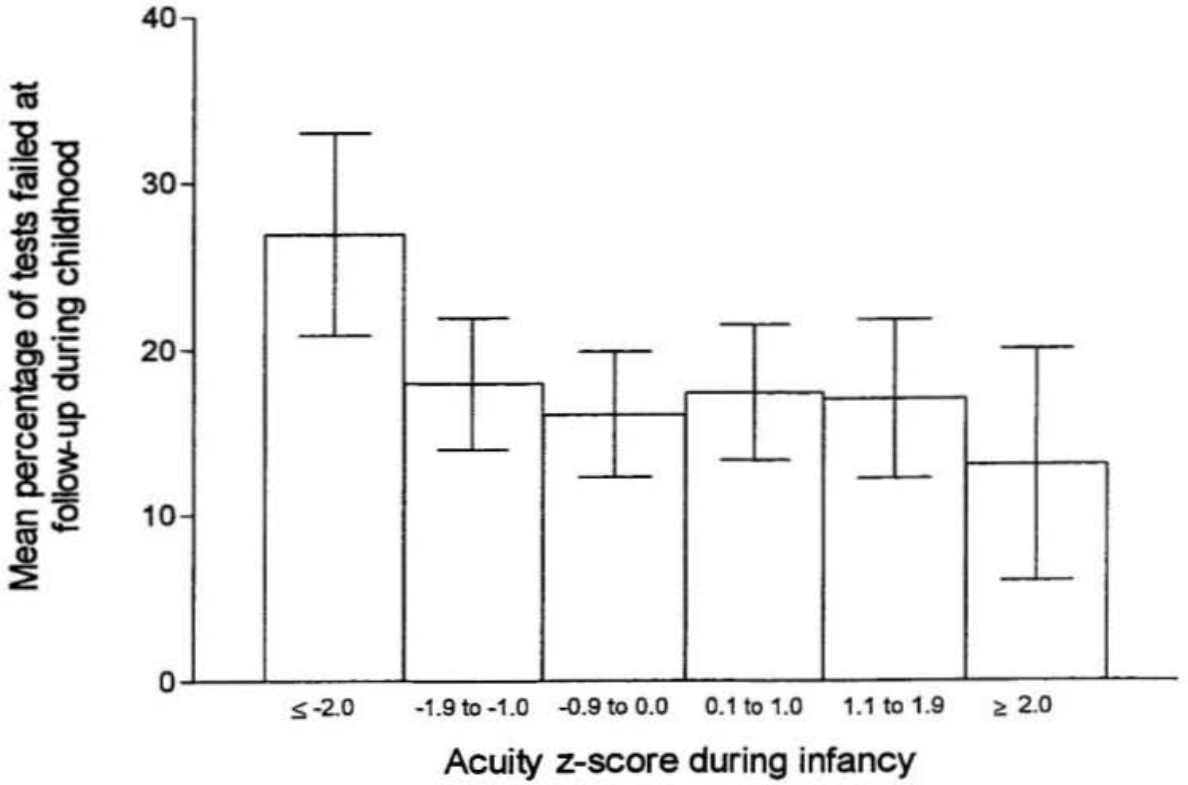

≥3501
3001-3500
2501-3000
2001-2500
1501-2000
1001-1500
501-1000
0
r_s= .212
Mean birth weight (grams)
Abnormal
Suspect
Normal
Overall binocular acuity estimate at follow-up during childhood

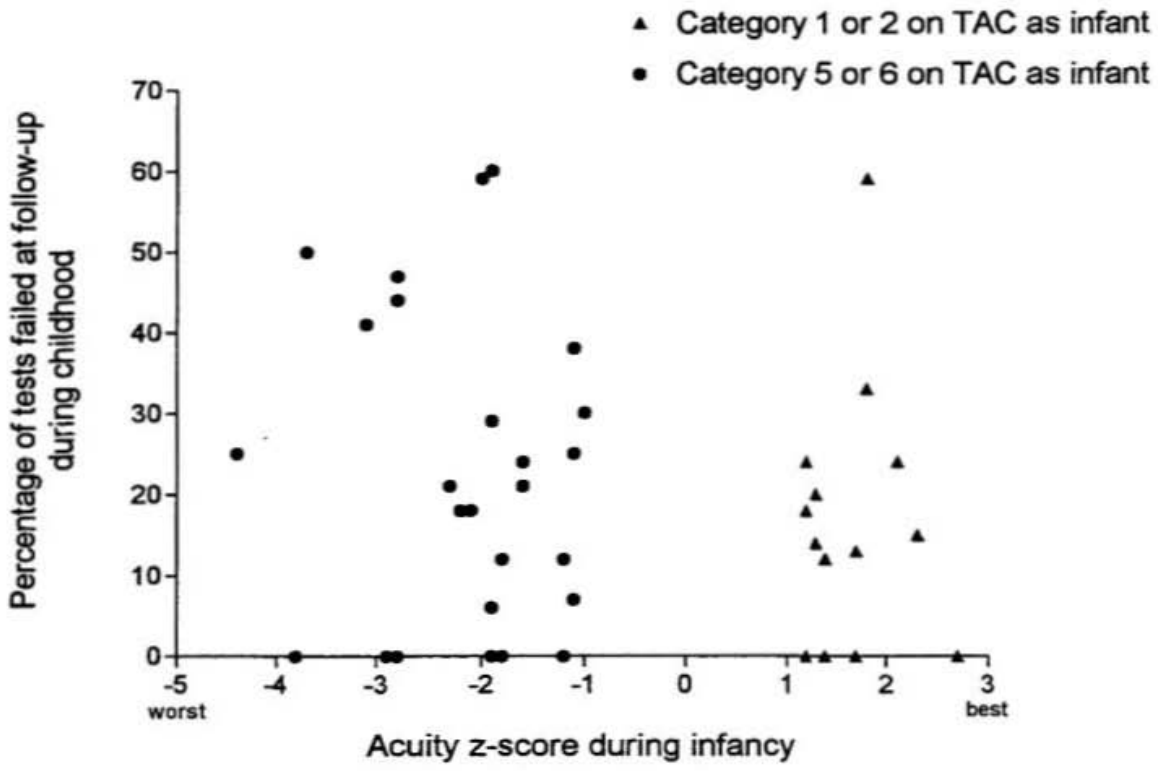

3001-3500
2501-3000
2001-2500
1501-2000
1001-1500
501-1000
0
Mean birth weight (grams)
r_s= .210
Abnormal
Suspect
Normal
Worst case acuity estimate at follow-up during childhood

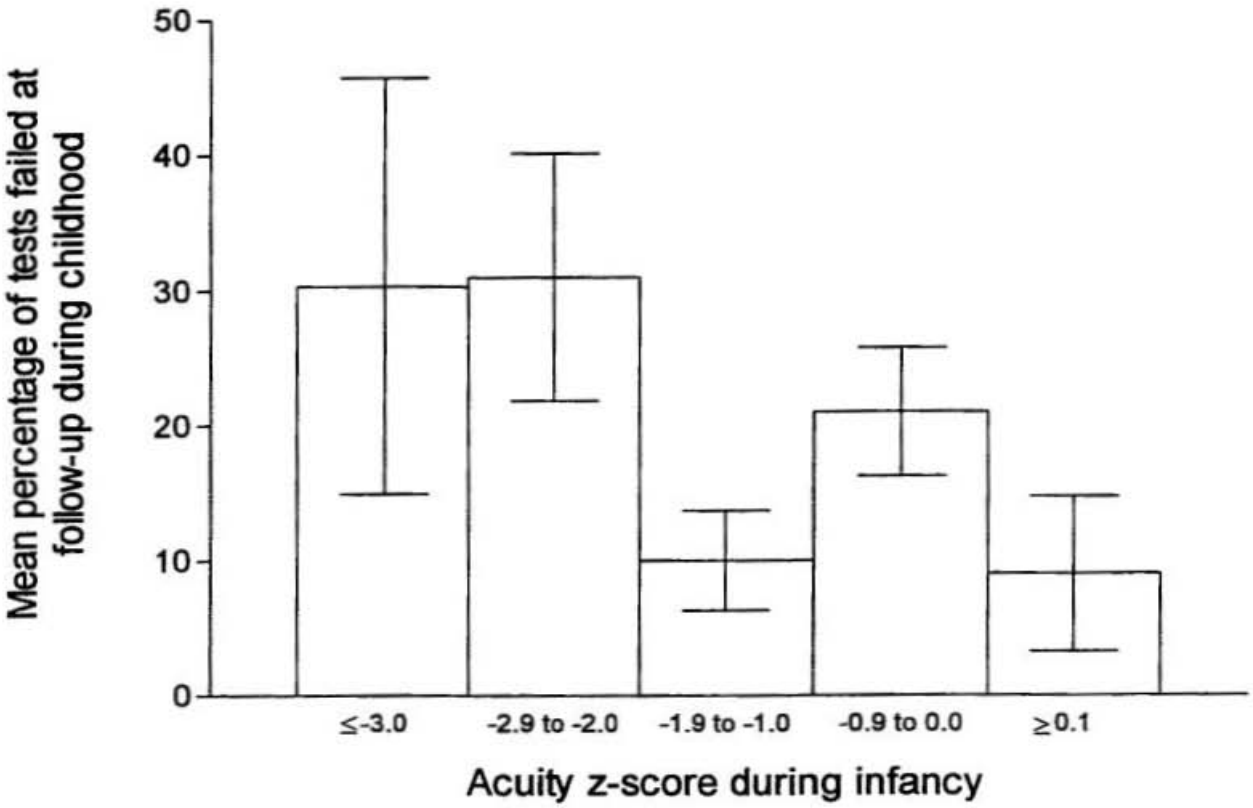

Mean percentage of tests failed at follow-up during childhood
30
20
10
0
≤ 29
30-34
35-39
≥ 40
Gestation (weeks)

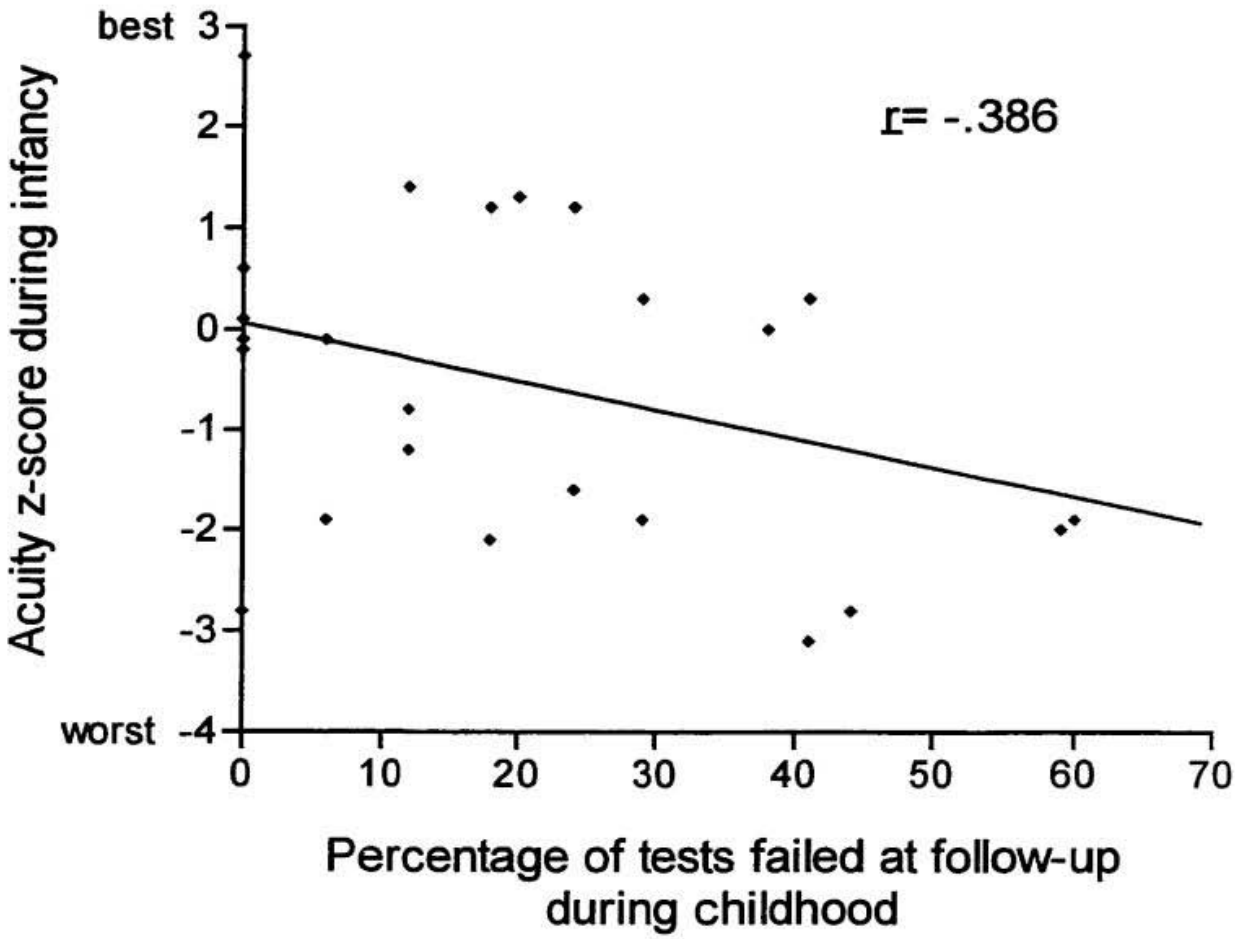

Mean categorical TAC acuity estimate during infancy
worst 6
5
4
3
2
best 1
Abnormal
Suspect
Normal
Overall binocular acuity estimate at follow-up during childhood


Mean percentage of tests failed at follow-up during childhood
30
20
10
0
≤ 80
81-90
91-100
101-110
111-120
≥ 121
Developmental Quotient (DQ) during infancy

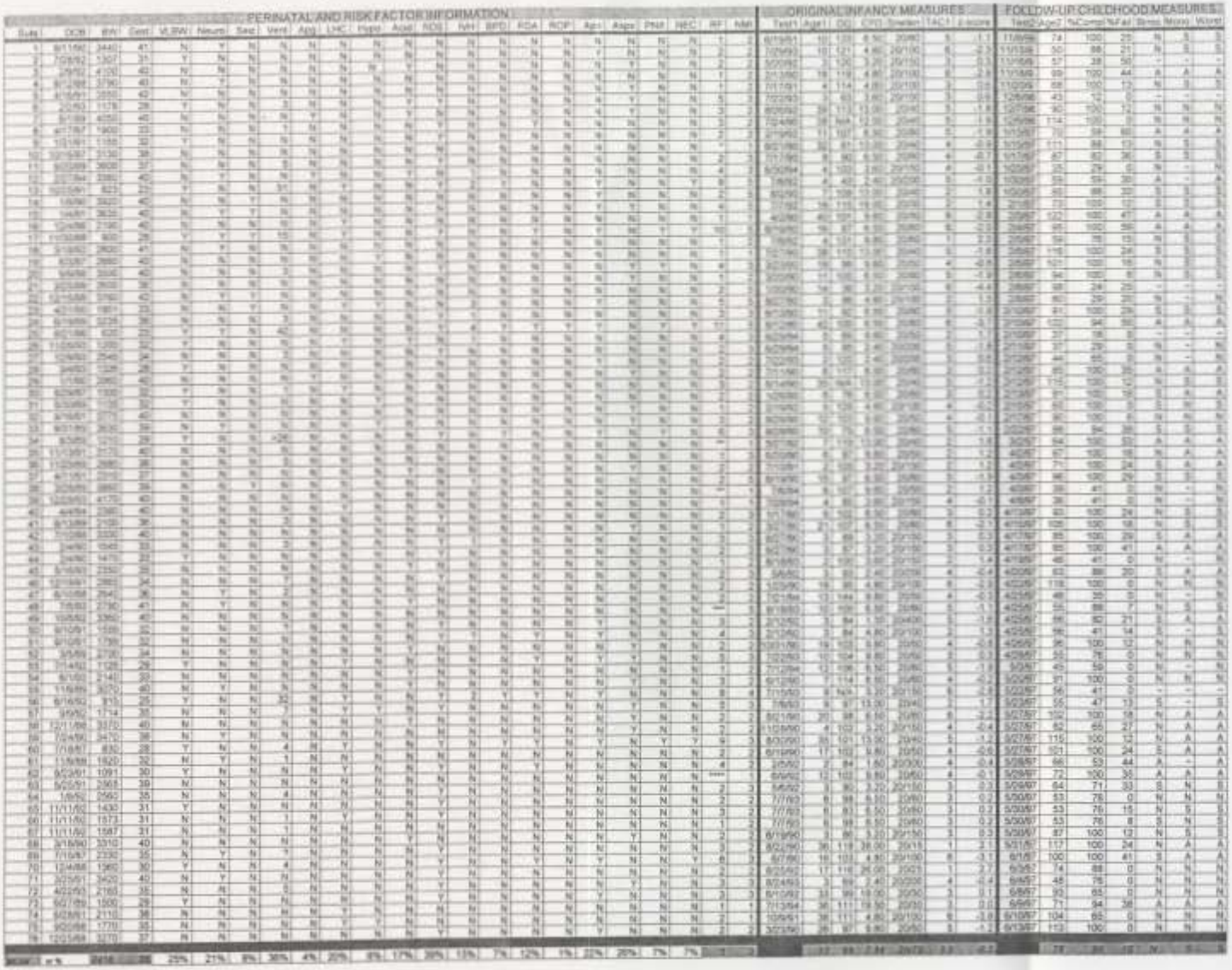

Mean percentage of tests failed at follow-up during childhood
40
30
20
10
0
≤ -2.0
-1.9 to -1.0
-0.9 to 0.0
0.1 to 1.0
1.1 to 1.9
≥ 2.0
Acuity z-score during infancy


Category 1 or 2 on TAC as infant
Category 5 or 6 on TAC as infant
Percentage of tests failed at follow-up during childhood
70
60
50
40
30
20
10
0
-5
worst
-4
-3
-2
-1
0
1
2
3
best
Acuity z-score during infancy


Mean percentage of tests failed at follow-up during childhood
50
40
30
20
10
0
≤-3.0
-2.9 to -2.0
-1.9 to -1.0
-0.9 to 0.0
≥0.1
Acuity z-score during infancy


best 3
2
1
0
-1
-2
-3
worst -4
r= -.386
Acuity z-score during infancy
0
10
20
30
40
50
60
70
Percentage of tests failed at follow-up during childhood

Appendix A Summary of At-risk Subjects' Perinatal and Risk Factor Information & Infancy and Childhood Measures



Note:

Subj	subject number
DOB	date of birth (mm/dd/yy)
BW	birth weight (grams)
Gest	gestation (weeks)
LBW	low birth weight (≤ 1500 grams; Yes/No)
Neuro	neurological signs (persisting beyond 6th hour after birth; Yes/No)
Seiz	seizures (anytime; Yes/No)
Vent	ventilation required (number of days/No)
Apg	low 5-minute Apgar score (≤ 5; Yes/No)
LHC	low head circumference (› 2 SD below normal for gestational age; Yes/No)
Hypo	hypoglycaemic (Yes/No)
Acid	metabolic acidosis (cord ph ‹ 7.2, bicarbonate value ‹ 14, base excess value more negative than −12; Yes/No)
RDS	respiratory distress syndrome (Yes/No)
IVH	intraventricular haemorrhage (Grade 1-4/No)
BPD	bronchopulmonary dysplasia (Yes/No)
PDA	patent ductus arteriosus (Yes/No)
ROP	retinopathy of prematurity (Yes/No)
Apn	apnea (Yes/No)
Aspx	clinical signs of asphyxia (Yes/No)
PNX	pneumothorax (Yes/No)
NEC	necrotizing enterocolitis (Yes/No)
RF	number of risk factors (1-11)
NMI	Neonatal Medical Index classification [1(best) to 5(worst)]
Test1	date of first test during infancy (mm/dd/yy)
Age1	age at first test (months)
DQ	development quotient (Griffith's Development Scale)
CPD	cycles per degree
Snellen	20/x
TAC1	assigned TAC category, based upon acuity norms [A(best) to F(worst)]
z-score	z-score, based upon TAC acuity estimate
Test2	date of follow-up test (mm/dd/yy)
Age2	age at follow-up test (months)
%Comp	percentage of tests completed at follow-up
%Fail	percentage of tests failed at follow-up (i.e., classified A/S)

Binoc	worst binocular acuity score
Mono	worst monocular acuity score
Worst	worst overall acuity score (binocular & monocular combined)

Y	Yes; present
N	No; absent (under Binoc/Mono columns, it means 'normal')
S	suspect
A	abnormal
?	present, but length/degree/grade unknown
-	data not available
*	low head circumference according to PPP standards, but not those of this study
**	hyperbilirubenemia
***	meningitis
****	seizures suspected, but not confirmed

Calculation of 'mean score' under Binoc, Mono and Worst columns

N (normal) scores 3
S (suspect) scores 2
A (abnormal) scores 1

If average is...	Then categorized as...	
2.66 - 3.00	N	(normal)
2.33 - 2.65	N -	(low end of normal range)
2.00 - 2.32	S +	(high end of suspect range)
1.66 - 1.99	S	(suspect)
1.33 - 1.65	S -	(low end of suspect range)
1.00 - 1.32	A	(abnormal)

Appendix B

CONSENT FORM

I, _____, give permission for my child, _____, to participate in this vision study being conducted by Heather L. Hall and Dr. Russell Adams of the Department of Psychology at Memorial University of Newfoundland. I have been informed that participation will involve completing a questionnaire about my son/daughter's visual, medical and educational history and allowing my child's vision to be assessed by Ms. Hall. This testing session will take approximately 45 minutes to complete.

Although I realize that this is not a full visual examination, should the researchers detect any problems with the aspects of my son/daughter's visions tested, I have been informed that I will be contacted within two weeks of the testing session. I also understand that the method of testing will involve my son/daughter looking at a series of charts and he/she will be required to identify the various letters/ symbols presented. At no time will any drops be put in my son/daughter's eyes, nor will any other invasive procedure be used.

I understand that the information given in the questionnaire and my son/ daughter's visual status will remain completely confidential and will not be made public in any way that he/she can be identified as a participant.

I realize that I will obtain a full explanation of the purpose of the research from the experimenter upon completion of the session.

I am also aware that my child's participation in this study is completely voluntary and that he/she may withdraw from the study at any time without consequence.

I have read the above statements and freely consent to my child's participation in this research.

Signed: _____

Date: _____

In the event that I have any complaints or concerns regarding this study, I understand that I am free to contact Dr. Russell Adams (737-2513) or, if this is not satisfactory, Dr. John Evans (737-8495), Head of the Department of Psychology.

Appendix C

Educational and Family Income Data Form

Subject #___

PLEASE COMPLETE THE FOLLOWING QUESTIONS.

BE ASSURED THAT YOUR ANSWERS WILL REMAIN STRICTLY CONFIDENTIAL AND NOT BE PAIRED WITH YOUR CHILD'S NAME IN ANY WAY.

Has your child ever repeated a grade? _____
Which grade? _____

Has your child ever been in a remedial program? _____
Grade? _____

Based on your child's last report card and teacher's comments, would he/she be rated as :
_ above average _ average _ below average

How would you describe your total family income:
_under $20,000
_$20,000 to $39,000
_$40,000 to $59,000
_ over $60,000

Appendix D

Vision and Medical History Form

DATE: _____
NAME: _____
ADDRESS: _____
PHONE NUMBER: _____
AGE AT TEST: _____
BW: _____ GEST: _____

RESEARCHER'S USE ONLY
SUBJECT ____
DATE OF PPP TEST _____
AGE AT PPP TEST _____
CATEGORY ____
RISK FACTORS _____

Any known vision problems? _____
Does your child require glasses or contact lenses? _____
For what condition? (e.g., near-sighted) _____
Power of lens (if known) _____
When does he/she wear them? (e.g. at school, watching TV) _____
_____
Has your child ever been seen by an eye doctor? _____
When? _____
Name and location of doctor. _____
Reason for assessment and result. _____
_____
When was your child's **last** visual assessment? _____
Name and location of doctor. _____
Reason for last assessment and result _____
_____
Have your child's eyes been tested by anyone else? _____
Name and location of examiner. _____
Reason for testing and result. _____
_____
Is there any family history of vision problems? (e.g., parent, sibling, other)
_____
Does your child have any other medical/developmental problems? _____
_____

To assist us in gathering information concerning your child's visual functioning history, would you be willing to allow us to contact his/her eye care specialist? If yes, please complete the form below.

Dear _____,

My son/daughter, _____, *has recently participated in a follow-up study being conducted at Memorial University.*

By signing this form, I am giving Dr. Russell Adams and his colleagues permission to obtain information from you regarding my son/daughter's ophthalmic history.

SIGNED: _____ *DATE:* _____

Memorial
University of Newfoundland

Department of Psychology

Appendix E

Letter to Eye Care Specialists

Date

Eye Care Specialist
Street Address
City, Province
Postal Code

Dear Dr. _____;

As we discussed on the phone, our research group is conducting a long-term follow-up investigation on the visual development of children, who at birth, experienced significant perinatal complications (e.g. extreme prematurity, very low birth weight, birth asphyxia, long periods of mechanical ventilation, neonatal hypoglycaemia, etc.). As infants, all of these patients were enrolled in the Provincial Perinatal Programme at the Janeway Hospital and were routinely tested for early physical, mental, motor, and neurological development. During that period, we also tested their visual acuity with a new technique which is based on eye movements and other visual behaviour. We are now interested in determining how those early measurements predict visual development in this high risk population several years later. Therefore, we have recently tested all of these children again with a battery of standard vision tests and are interested in correlating these findings with the earlier measurements.

In the interim, many of these children have seen eye care specialists such as yourself and are regular patients. To help interpret our findings we need to be provided with independent information about each child's refractive status as well as diagnoses of ocular disorders. We have provided a simple form to help make the task as simple as possible. Note that all parents of the children are aware of our request and have signed a permission slip. These will be provided to you when we visit your office to deliver the names of the patients and the accompanying forms.

This information is vital to the research and we appreciate greatly the time required by you to do this. We will acknowledge your contribution in the published report of this work (likely in a year or two) as well as at any scientific or clinical meetings at which the work will appear. We will also send you copies of any publications arising from this research.

In closing, I would also like to take this opportunity to say that we always welcome collaboration with clinicians such as yourself. Our particular expertise is in the area of vision science (spatial vision, colour vision, visual physiology) with a special interest in pediatric issues. Although our research is diverse, a project that we have devoted much time to over the past few years, is to attempt to develop new and more efficient tests for assessing early visual functioning. The goal of this work is to provide better and earlier screening tools for ocular and neurological disease, an endeavour which has broad scientific and clinical implications. If you have any research ideas (half or fully-baked), or even interesting patients (young or old) that you might want to discuss, please call. Also feel free to contact me if you have any other questions about the present study. Thanks.

Sincerely,

Russell J. Adams, Ph.D.
Professor of Psychology

Appendix F

Ophthalmic History Form

Name: _____ D.O.B.: _____ Last exam: _____

INSTRUCTIONS: Please describe or check off any identified ocular diagnoses.

	OS	OD
Refractive Status 1. sphere 2. cylinder 3. axis	_____ D _____ D _____	_____ D _____ D _____
Visual Acuity	20/____	20/____
Stereopsis/Depth Perception	normal ____ absent ____ impaired ____	
Strabismus	esotropia ____ exotropia ____	esotropia ____ exotropia ____
Nystagmus		
Other eye movement/ alignment disorders (describe)		
Cataracts (describe)		
Other opacities in ocular media (describe)		
Retinal abnormalities (describe)		
Neuro-ophthalmic disorders (describe)		
Other diagnoses		

Thank you

Appendix G

Data Sheet

Subject #_____

CONTRAST SENSITIVITY (10') randomize rows; mistake & back
A__ B__ C__ D__ E__

NEAR TUMBLING E (16') alternate with far; 2 mistakes & back
BIN 20/__ LEFT 20/__ RIGHT 20/__
NEAR HOTV (14') numbers only
BIN 20/__ LEFT 20/__ RIGHT 20/__

FAR TUMBLING E (10') alternate with near; 2 mistakes & back
BIN 20/__ LEFT 20/__ RIGHT 20/__
FAR SNELLEN (10')
BIN 20/__ LEFT 20/__ RIGHT 20/__

TELLER ACUITY CARDS (84cm, then 168 cm)
20/__ __cpd

ISHIHARA COLOUR PLATES (50 cm) #38-26 tracing

26O__	28__	32__	36__
26P__	29__	33__	37__
27O__	30__	34__	38__
27P__	31__	35__	

STEREO FLY TEST (16') glasses on before show pictures
Fly __
Animals: cat__ rabbit__ monkey__ _____
Circles: 1__ 2__ 3__ 4__ 5__ 6__ 7__ 8__ 9__ _____

VISION DISK 2 trials each side (averaged)
Left ___ ___ average ____
Right ___ ___ average ____

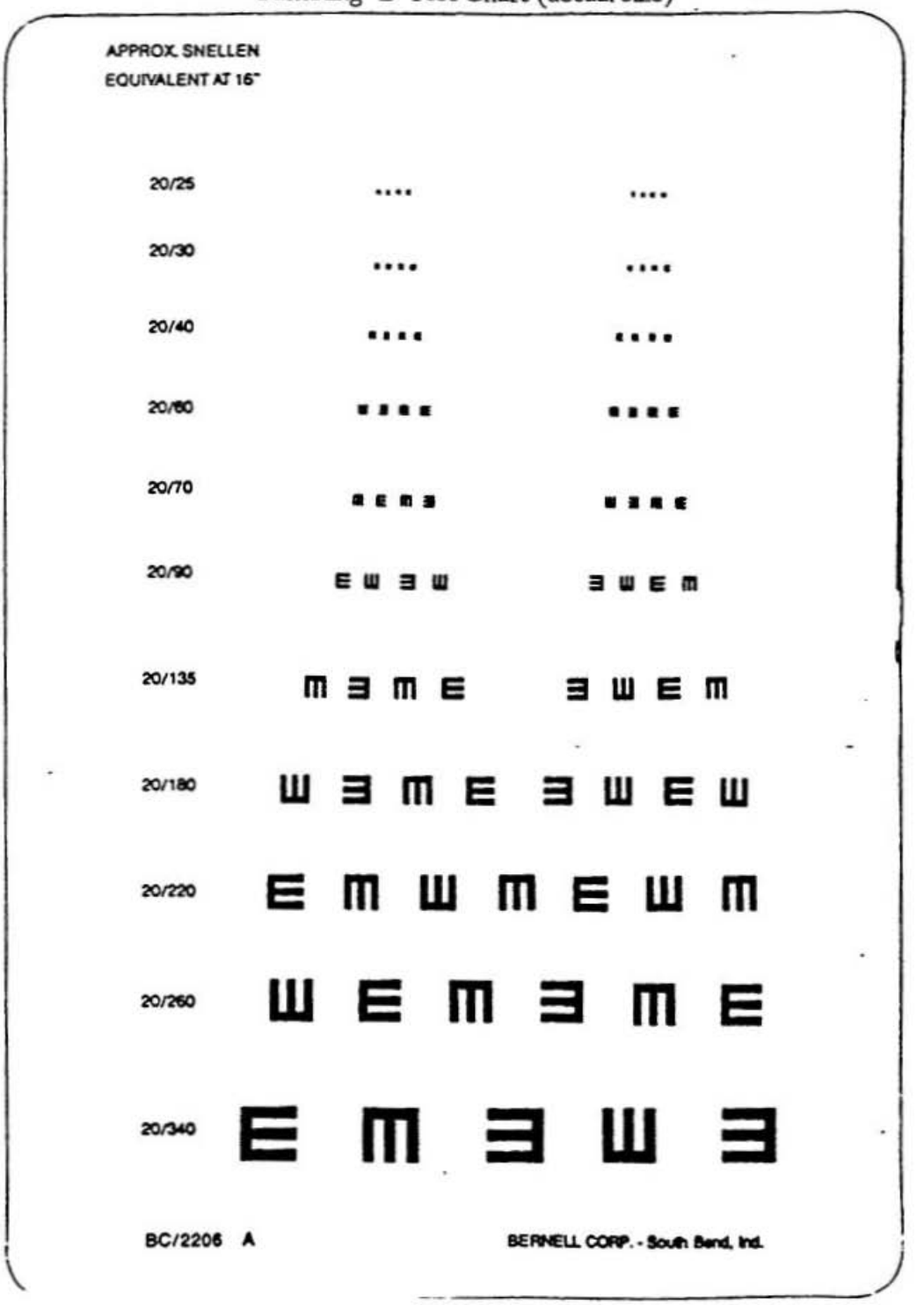
BROKEN WHEEL (10', if 20/20, then 20' and 15' with 20/20 card)
BIN 20/__ 20'__ 15'__

LIGHT EXAM
reflection _____
converging_____
tracking _____

ASTIGMATISM (20')
yes __ no __
if yes, angle(s) _____

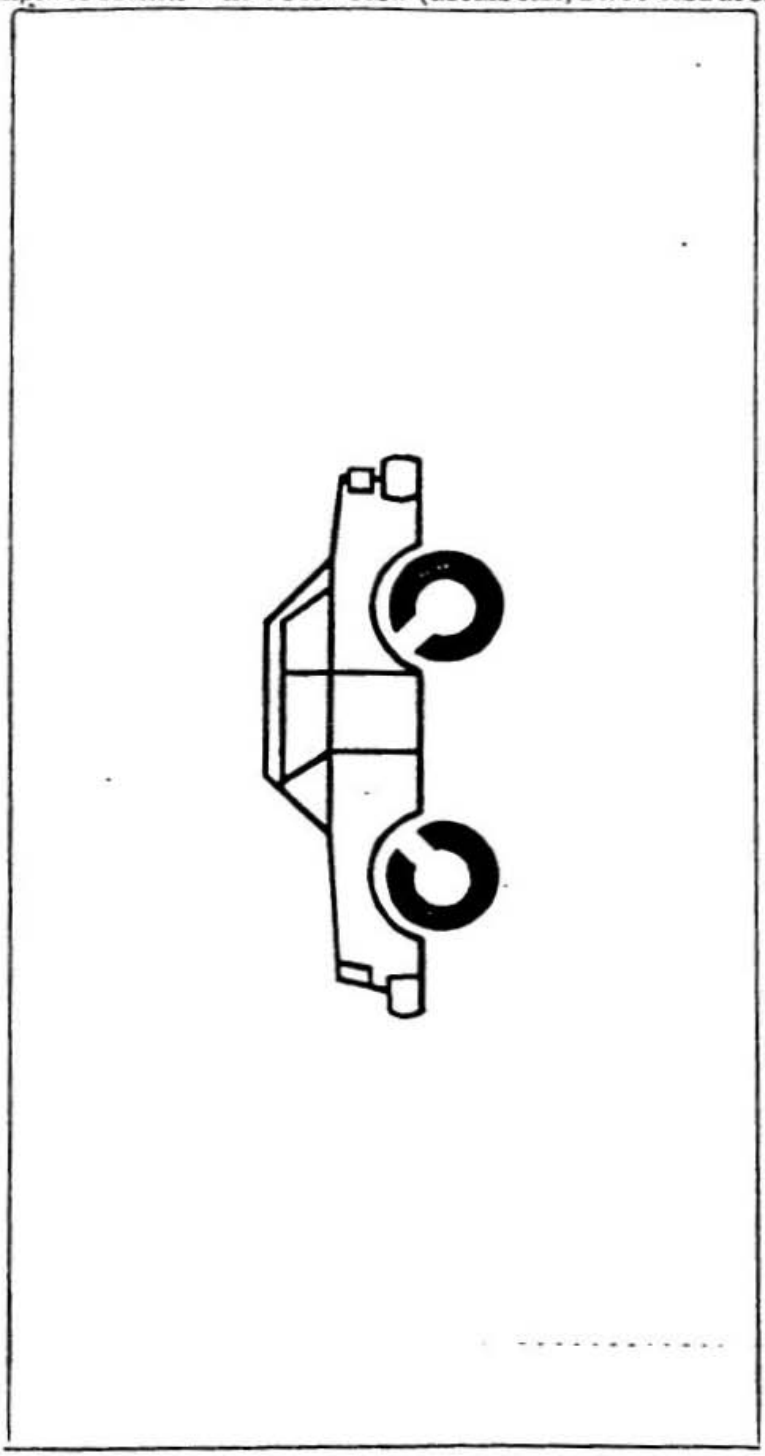
Appendix H

Tumbling "E" Test Chart (actual size)



Appendix I

Example of Broken Wheel Test Card (actual size; 20/80 card at 3m)



Appendix J

Debriefing Form (at-risk participants)

Even though we have a number of tests for assessing an infant's *current* visual status, we don't know whether these tests can *predict* the visual status of the same child at a later age. This is especially true for infants who are low birth weight, premature and/or who experienced some other medical risk factor or complication around the time of birth. The primary goal of this study is to determine whether or not a single test during infancy with the Teller Acuity Card test can make these predictions. All of the children taking part in this study were tested as infants or as young children with the Teller Acuity Cards (the 'stripe' test that you probably remember).

As a secondary goal of this study, we are also interested in trying to evaluate which of the risk factors that your baby may have experienced around birth best predicts visual development.

While the Teller Acuity Cards are widely used and have become a standard in ophthalmic practice, their effectiveness has not yet been tested properly. This study is designed to be a first step in this direction. If the overall results of this study suggest that scores obtained in infancy are predictive of later functioning, then this will be an indication that this test is one that we should continue using for this purpose. This result would indicate that the test is a useful screening device during infancy. If the results, however, suggest that the test is not a good predictor, then this may be an indication that a more suitable test should be used or developed.

If you are interested in finding out more about the Teller Acuity Cards, the following articles will provide you with a good review of the procedure and its history. Articles concerning other longitudinal and predictive-type research projects are also listed.

Korner, A. F., Stevenson, D. K., Kraemer, H. C., Spiker, D., Scott, D. K., Constantinou, J., & Dimiceli, S. (1993). Prediction of the development of low birth weight preterm infants by a new neonatal medical index. Developmental and Behavioral Pediatrics, 14(2), 106-111.

Courage, M. L., & Adams, R. J. (1990). Visual acuity assessment from birth to three years using the acuity card procedure: Cross-sectional and longitudinal samples. Optometry and Vision Sciences, 67(9), 713-718.

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

Thank you for your participation

Appendix K

Debriefing Form (control participants)

Even though we have a number of tests for assessing an infant's *current* visual status, we don't know whether these tests can *predict* the visual status of the same child at a later age. This is especially true for infants who are low birth weight, premature and/or who experienced some other medical risk factor or complication around the time of birth. Over the past year we have tested approximately 80 children who were high-risk infants. The primary goal of this study is to determine whether or not a single test during infancy with the Teller Acuity Card test can make these predictions. All of the children taking part in this phase of the study were normal, healthy infants who did not experience any major birth complications. They will provide us with an important comparison group for the high-risk infants we recently tested.

Thank you for your participation

Appendix L

Test Norms and Category Cut-offs

1) Acuity norms (Canadian ophthalmologists' standards)

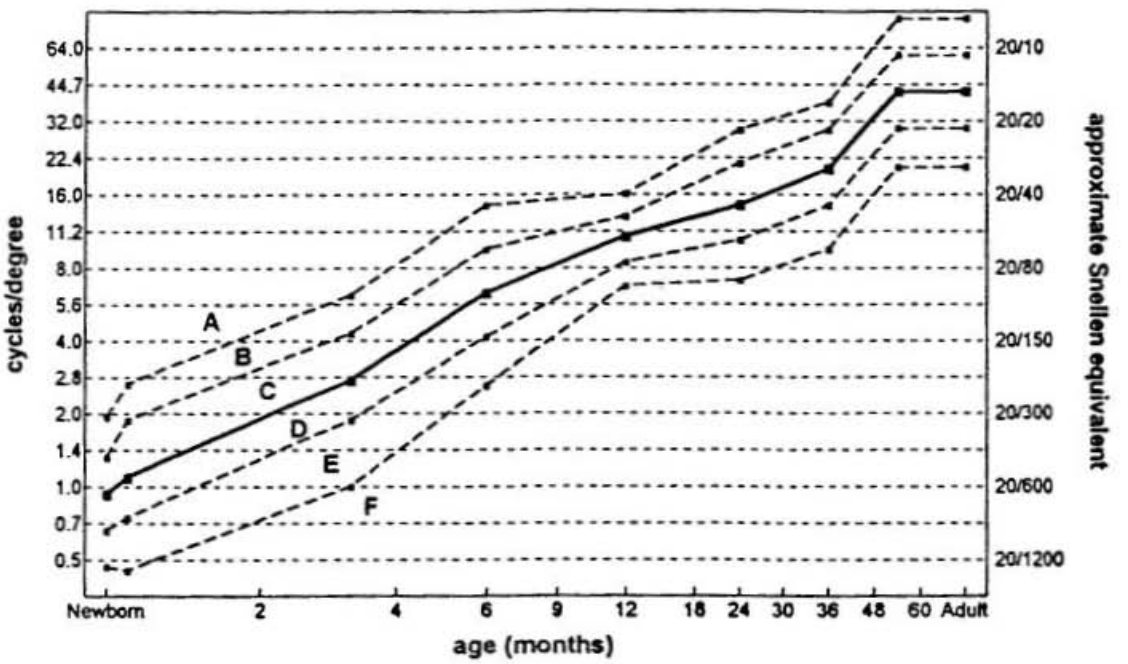
(used for near & distance recognition acuity)

Age (years)	Suspect[a]	Abnormal
3	20/40	20/50 or worse
4	20/30	20/40 or worse
5	20/25	20/30 or worse
6	20/25	20/30 or worse
7	20/25	20/30 or worse
8	20/25	20/30 or worse
9+	20/25	20/30 or worse

Note. [a]Any score better than the one listed for that age would be classified as normal.

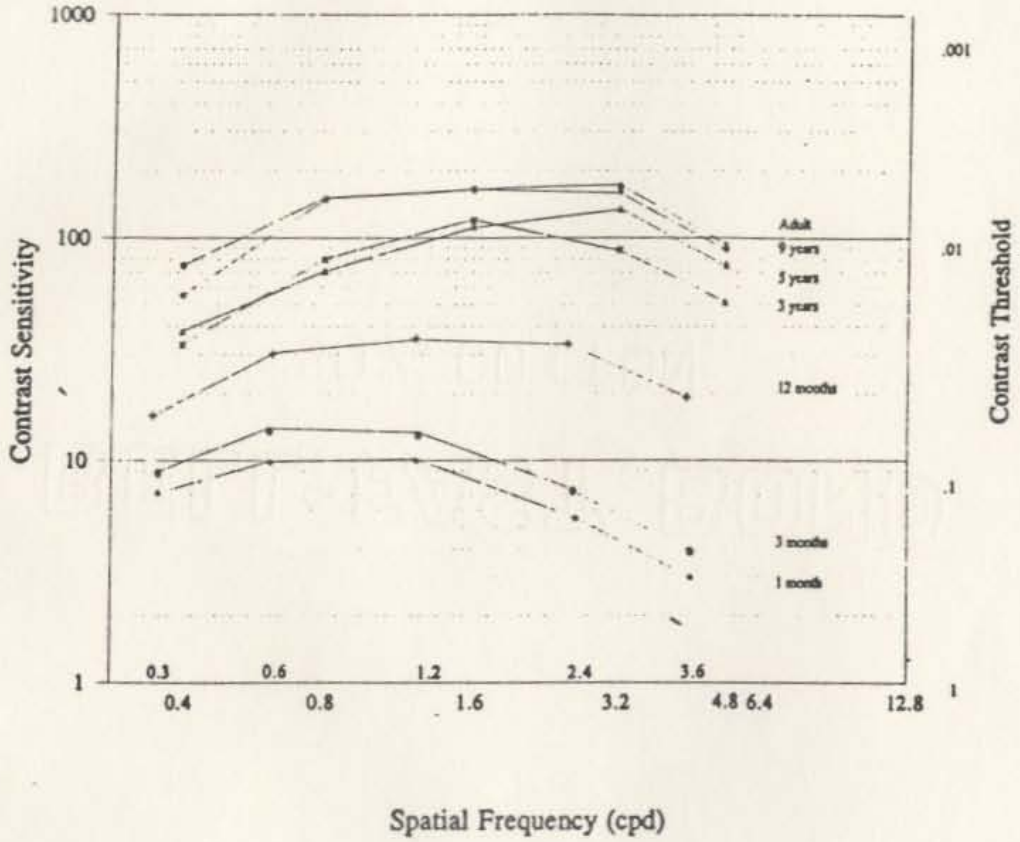
2) TAC norms (from Courage & Adams, 1990)

(solid line represents mean; dotted lines represent standard deviations; "Normal": score falls within regions of Categories A-D; "Suspect": Category E; "Abnormal": Category F))



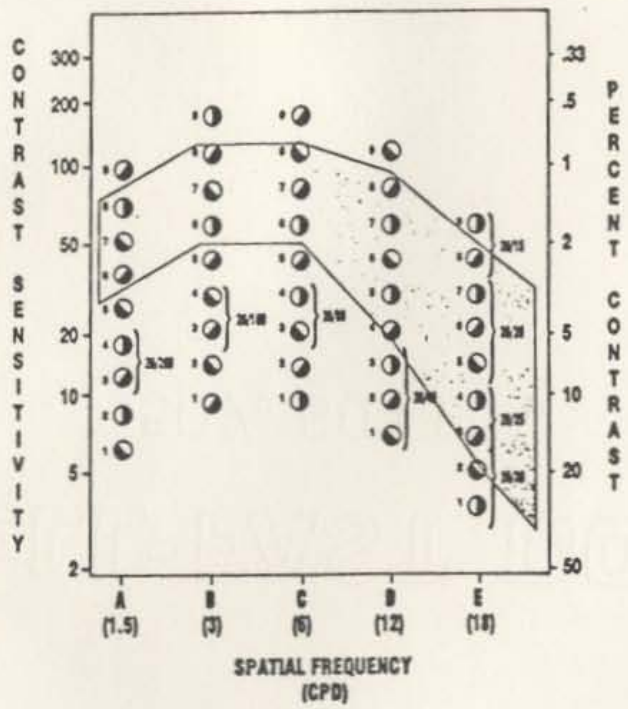
3) Contrast Sensitivity Norms

for participants ≥ 5 years of age (from Courage, Piercey & Adams, 1997)



for subjects < 5 years of age (Vistech Consultants Inc., Dayton, OH)

(normal range of contrast sensitivity is shown in the shaded area)



4) Broken Wheel Test norms (from Preschool Enrichment Team, Inc., Holyoke, MA)

Age (years)	Pass (Normal)	Fail (Abnormal)
3	20/40 or better	20/50 or worse
4	20/30 or better	20/40 or worse
5	20/30 or better	20/40 or worse
6	20/30 or better	20/40 or worse
7+	20/25 or better	20/30 or worse

5) Monocular Peripheral Vision norms (Canadian ophthalmologist's standards)

if ≥ 85°, then classify as normal
if < 85°, but ≥ 80°, then classify as suspect
if < 80°, then classify as abnormal

6) Ishihara Colour Plates (38 Plates Edition) (from Kanehara & Co., Tokyo)

Number of Plate	Normal Person	Person with Red-Green Deficiencies				Person with Total Colour Blindness and Weakness
1	12	12				12
2	8	3				×
3	6	5				×
4	29	70				×
5	57	35				×
6	5	2				×
7	3	5				×
8	15	17				×
9	74	21				×
10	2	×				×
11	6	×				×
12	97	×				×
13	45	×				×
14	5	×				×
15	7	×				×
16	16	×				×
17	73	×				×
18	×	5				×
19	×	2				×
20	×	45				×
21	×	73				×
		Protan		Deutan		
		Strong	Mild	Strong	Mild	
22	26	6	(2)6	2	2(6)	
23	42	2	(4)2	4	4(2)	
24	35	5	(3)5	3	3(5)	
25	96	6	(9)6	9	9(6)	

The mark × shows that the plate cannot be read. Blank space denotes that the reading is indefinite. The numerals in parenthesis show that they can be read but they are comparatively unclear.

7) Stereo Vision norms (Circle Test)[a] (from Tatsumi & Tahira, 1972)

Age (years)	Normal[b]	Suspect[b]	Abnormal[b]
2	≥ 800	0	--
3	≥ 400	800	0
4	≥ 140	400-200	800-0
5	≥ 140	400-200	800-0
6	≥ 80	200-100	400-0
7	≥ 50	80-60	100-0
8	≥ 50	100-60	140-0
9	≥ 50	100-60	100-0
10+	≥ 50	60	80-0

Note. [a]there were nine clusters of circles in the test. [b]expressed as minutes of arc.