Global Motion Perception in 2-Year-Old Children: A Method for Psychophysical Assessment and Relationships With Clinical Measures of Visual Function

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Purpose. We developed and validated a technique for measuring global motion perception in 2-year-old children, and assessed the relationship between global motion perception and other measures of visual function.

Methods. Random dot kinematogram (RDK) stimuli were used to measure motion coherence thresholds in 366 children at risk of neurodevelopmental problems at 24 ± 1 months of age. RDKs of variable coherence were presented and eye movements were analyzed offline to grade the direction of the optokinetic reflex (OKR) for each trial. Motion coherence thresholds were calculated by fitting psychometric functions to the resulting datasets. Test–retest reliability was assessed in 15 children, and motion coherence thresholds were measured in a group of 10 adults using OKR and behavioral responses. Standard age-appropriate optometric tests also were performed.

Results. Motion coherence thresholds were measured successfully in 336 (91.8%) children using the OKR technique, but only 31 (8.5%) using behavioral responses. The mean threshold was 41.7 ± 13.5% for 2-year-old children and 3.3 ± 1.2% for adults. Within-assessor reliability and test–retest reliability were high in children. Children's motion coherence thresholds were significantly correlated with stereoacuity (LANG I & II test, $\rho = 0.29$, $P < 0.001$; Frisby, $\rho = 0.17$, $P = 0.022$), but not with binocular visual acuity ($\rho = 0.11$, $P = 0.07$). In adults OKR and behavioral motion coherence thresholds were highly correlated (intraclass correlation = 0.81, $P = 0.001$).

Conclusions. Global motion perception can be measured in 2-year-old children using the OKR. This technique is reliable and data from adults suggest that motion coherence thresholds based on the OKR are related to motion perception. Global motion perception was related to stereoacuity in children.

Keywords: motion coherence threshold, random-dot-kinematogram, vision, optokinetic nystagmus, dorsal stream

The dorsal visual cortical stream, which includes motion sensitive extrastriate area V5/MT, is thought to be particularly vulnerable to abnormal development.[1–5] For example, specific deficits in the perception of global motion, which requires the integration of multiple local motion signals, have been reported in children with Williams syndrome,[6] developmental dyslexia,[7,8] cerebral palsy,[9] and a history of preterm birth[10,11] (see prior reviews[1,3]). Measurements of global motion perception typically use random dot kinematograms (RDK, Fig. 1). These stimuli consist of two populations of moving dots, a signal population that moves in a common, coherent direction and a noise population that moves randomly.[12] The observer's task is to discriminate the direction of the signal dots and the signal-to-noise ratio is varied to estimate the percentage of signal dots required for a particular level of task performance. This is known as the motion coherence threshold. Evidence that this process involves dorsal extrastriate area V5/MT has been provided by neurophysiologic studies linking global motion perception to neural responses in primate MT.[13–15] Relationships between V5/MT activity and global motion perception also have been found in humans using brain imaging techniques.[16–21] Furthermore, studies in animals and humans have shown that lesions[12,22–27] and stimulation[28,29] of V5/MT can selectively influence global motion perception. Therefore, as global motion perception is likely to rely on processing in V5/MT, it may provide a useful measure of dorsal cortical stream development in children.

Global motion perception emerges at 1 to 3 months of age[30–32] and continues to develop throughout childhood.[9,10,33–36] However, the development of global motion perception in early childhood is not well understood and currently no data are available for children between the ages of 7 months and 3.5 years. This may be due to the difficulties involved in measuring visual function in children of this age. Preferential looking techniques, while still possible,[37] can become more challenging as children reach 12 to 18 months of age,[38–43] and tasks that require behavioral responses are feasible only when the requisite cognitive and language skills

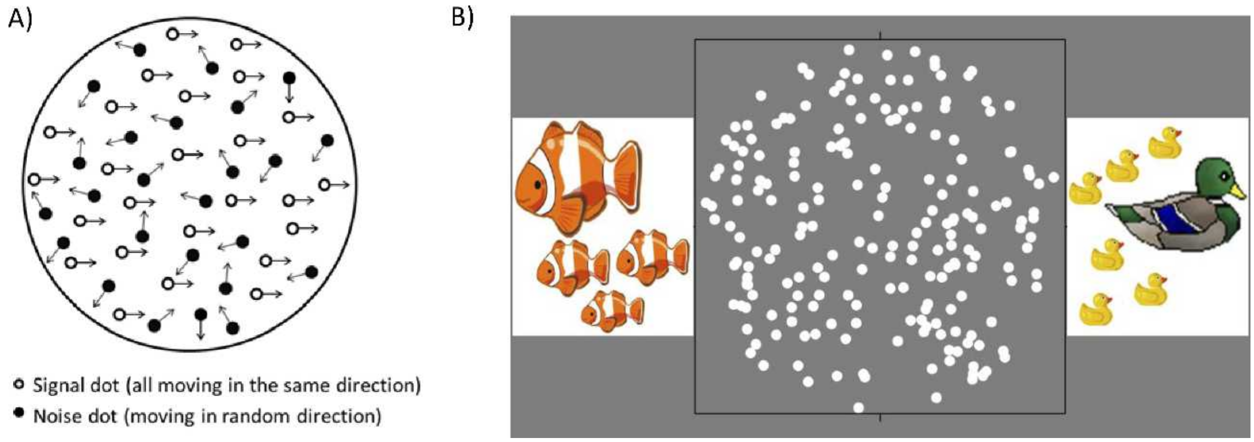

Figure 1. The RDK stimulus. (**A**) A schematic of the RDK stimulus depicting 50% coherence. *Open circles* represent signal dots and *filled circles* represent noise dots. The *arrows* illustrate the motion direction of each dot. Half of the dots are signal dots (all moving to the right) and the other half are noise dots (moving in random directions). (**B**) A single frame of the RDK stimulus used in the study.

have developed, which typically is after the age of 36 months.[44–49]

The aim of our study was to develop and validate a technique for assessing global motion perception that could be applied to 2-year-old children. We used an approach that allowed for the optokinetic reflex (OKR) and behavioral responses to be recorded, and we assessed motion coherence thresholds using a modified method of constant stimuli. The OKR occurs in response to a continuously moving stimulus and is characterized by pursuit eye movements in one direction interleaved with saccadic refixation eye movements in the opposite direction.[50] The OKR has been used previously to measure global motion perception in children aged 6 to 27 weeks.[30,51] However, the use of this technique has not been reported for 2-year-old children, to our knowledge. Indeed, as mentioned above, there are no previous reports of global motion coherence thresholds in 2-year-olds, possibly due to the difficulties in obtaining reliable psychophysical measurements from children of this age.

Materials and Methods

Participants

Data were collected from 366 children at 24 ± 1 months of corrected age. The children were born with risk factors for neonatal hypoglycemia and were part of the longitudinal Children with Hypoglycaemia and their Later Development (CHYLD) study. Risk factors for neonatal hypoglycemia included being born small (<10th percentile or <2.5 kg) or large (>90th percentile or >4.5 kg), infant of a diabetic mother, preterm (<37 weeks' gestation) or other (e.g., poor feeding). Only half of the cohort actually had experienced neonatal hypoglycemia, and in most cases this was mild and transient.[52] We currently are investigating whether neonatal hypoglycemia had any effect on visual development within this cohort as part of the longitudinal CHYLD study. However, the goal of this particular investigation was to assess whether global motion perception could be measured accurately in these children at 2 years of age. To determine test–retest reliability, 15 children aged 21 to 27 months, 11 of whom were not part of the CHYLD study cohort, were assessed on two occasions separated by at least one day (range, 1–114 days). Ten adults with normal vision (mean age, 29.7 years; range, 26–35 years) also were assessed. All study protocols were done in accordance with the Declaration of Helsinki, and were approved by the Northern Y Regional Health and Disability Ethics Committee or the University of Auckland Human Participants Ethics Committee.

Stimuli

The global motion stimulus (Fig. 1) was an RDK presented on a cathode ray tube monitor (Dell E772p [Dell, Plano, TX] or HP 7540 [Hewlett-Packard Company, Palo Alto, CA], 1280 × 1024 resolution, 60 Hz refresh rate) placed 60 cm from the observer. The stimuli were generated using MATLAB (MathWorks, Natick, MA) and the Psychophysics Toolbox.[53–55] The RDK was presented within a circular stimulus aperture with a radius of 8.3°, and was made up of 250 white dots (138 cd/m^2) presented on a grey background (42 cd/m^2, dot density = 1.16 dots/deg^2). Each dot had a diameter of 0.5°, a speed of 8°/s (generated by displacing each dot by 0.13° on every frame), and a limited lifetime defined as a 5% chance of disappearing on each frame and being redrawn in a random location. The noise dots had a constant speed and direction. The duration of each RDK presentation was 8 seconds (480 frames per trial). Pictures were positioned on each side of the RDK stimulus to facilitate behavioral responses.

Procedure

For children from the CHYLD study cohort, measurements of global motion perception were made as part of a comprehensive developmental assessment. All psychophysical measurements were conducted in a well-lit room with minimal distractions. Eye movements were recorded at 50 Hz using a digital high definition camera (Sony HDR-CX7EK; Sony Corporation, Tokyo, Japan) placed to the left of the monitor with the zoom set so that the participant's head filled the frame.

Before the threshold measurement, training was conducted in two stages. First, the child was asked to follow a single dot with a finger and indicate which of the pictures the dot was approaching. This procedure then was repeated with a 100% coherent RDK stimulus. During threshold measurement a flashing fixation point accompanied by a beeping sound was presented in the center of the screen to attract the child's attention. Each trial then was initiated by the experimenter when the child was looking at the screen. During a trial, the RDK stimulus was presented for 8 seconds at a fixed level of coherence. Signal dot direction (left or right) was randomized

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TABLE. Tests and Testing Distances Used in the Optometric Assessment Along With Expected Norms for 2-Year-Old Children

Visual Attribute	Test	Testing Distance	Expected Norms for 2-Year-Old Children
Ocular health screening	External ocular inspection	–	No ocular pathology
	Red reflex testing	–	Normal red reflexes
	Pupillary reflex testing	–	Normal direct and consensual pupillary reflexes to light
Ocular alignment	Cover test	25 cm fixation target	No movement
	Hirschberg's corneal reflex	–	Symmetrical corneal reflexes
Ocular motility	Smooth pursuit to a moving target	30 to 40cm	Smooth movement without restrictions
	Near point of convergence	–	No established normative value
Stereopsis	Frisby Near Stereotest (distributed by Haag-Streit UK, Ltd, Sheffield, UK)	30 cm moving to 60 cm	No established normative value. Pass (demonstrates stereopsis) rate of 90 to 40%[38,49]
	LANG stereotest I and II (distributed by LANG-STEREO TESTAG, Forch, Switzerland)	40 cm	No established normative value. Pass (demonstrates stereopsis) rate of 90 to 74%[38,49,57,58]
Monocular and binocular visual acuity	Cardiff Acuity Cards (distributed by Richmond Products, Albuquerque, NM)	100 cm (or 50 cm if unsuccessful at 100 cm)	Monocular: 0.6–0.1 logMAR Binocular: 0.5–0.0 logMAR Interocular difference: $<$0.1 logMAR[59]
Motor fusion and suppression	20^{Δ} Base out prism test	25 cm fixation target	Fusional convergence eye movements
Refractive error screening (noncycloplegic)	Distance retinoscopy	$\geq$3 m fixation target	Mean sphere: ≥ -3.0 D and $\leq +1.5$ D
	Suresight handheld autorefractor (Welch Allyn, Skaneateles Falls, NY)		Anisometropia: $<$1.5 D in any meridian Astigmatism: $<$2.0 D any axis[60–62]

The tests were attempted in the listed order when possible.

for each trial. Coherence levels of 100%, 84%, 68%, 52%, 36%, and 20% were presented in descending order across consecutive trials and the sequence was repeated until the child could no longer be encouraged to look at the monitor. Children were asked to indicate the direction in which most of the dots were moving by pointing at and/or naming one of the pictures. After every five trials, brightly colored animations accompanied by music were presented to retain attention. Coherence levels for adult testing were fixed at 20%, 12%, 8%, 6%, 4%, and 2% to avoid ceiling effects. Adults completed 10 trials per level of coherence (60 trials in total).

Threshold Calculation

Behavioral and OKR responses were collected for each trial. Video recordings of OKR responses were assessed offline by an experienced assessor (TYY) who graded the OKR for each trial as "leftward," "rightward," or "no OKR" following a three-alternative forced choice procedure. The child's behavioral responses also were recorded as either "left," "right," or "no response." Trials were excluded if the child's eyes were not clearly visible (e.g., if the child had moved out of the video frame), the child was not looking at the screen, or the child's parent/guardian prompted the child with the correct answer. Adult participants provided behavioral responses following a two alternative forced choice procedure.

Motion coherence thresholds were calculated separately for OKR and behavioral responses. Only datasets with more than 15 observations (a minimum of 3 per level of coherence for a minimum of 5 levels of coherence) were analyzed. For the OKR data, a proportion correct was calculated for each coherence level based on the direction of the OKR reported by the video recording assessor. Proportion correct values then were fit with a Weibull function using the Palamedes toolbox for Matlab,[56] which also provided estimates of threshold (63% correct), slope, and goodness of fit using a bootstrap procedure.

Optometric Assessment

The optometric assessment, performed after the motion coherence threshold measurement, included tests of ocular motility, ocular health, and visual function (see Table).

Statistical Analysis

Testability was calculated as the percentage of children for whom successful measurements were made with reference to the number of children for whom the test was attempted. Within-assessor reliability and test–retest reliability were evaluated using paired-samples *t*-tests and single measures intraclass correlations. Correlations between different visual function measurements were evaluated using Spearman's ρ or Pearson's R correlation coefficients if the assumptions for parametric tests were met. Means are reported with associated standard deviations. When a child failed to demonstrate stereopsis, we were unable to differentiate between whether the child had no stereopsis or could not perform the test. Therefore, only successful measures were included in the reported means and statistical tests.

RESULTS

Testability and Reliability in 2-Year-Old Children

Motion coherence thresholds were measured successfully for 336 of 366 (91.8%) 2-year-old children using the OKR, which was higher than the optometry tests that required subjective

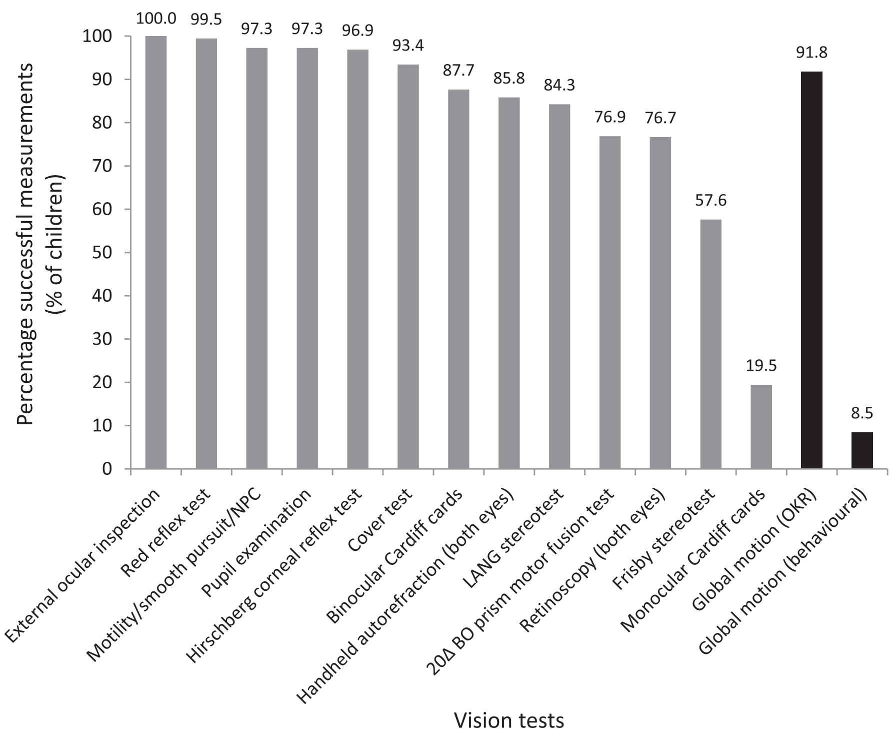

Figure 2. Percentage of successful measurements for each of the clinical vision tests and global motion measurements for 2-year-old children.

responses from the child (Fig. 2). The average number of RDK trials completed was 59 ± 16 and the average duration of the measurement per child was 18.6 ± 7.6 min. Behavioral motion coherence thresholds could be estimated only for 31 (8.5%) children.

To evaluate within-assessor reliability, 14 randomly selected OKR datasets were reanalyzed at least 6 months after the original analysis. The threshold results did not differ significantly between the first and second analysis (average difference = 1.47%, 95% confidence interval [CI] −3.56–0.62, t_{13} = 1.5, P = 0.15) and the single measures intraclass correlation was 0.96 (95% CI = 0.87–0.99, $P < 0.001$), reflecting "almost perfect" reliability.[63]

Test–retest reliability for the 15 children assessed on two separate days was analyzed using only the thresholds derived from OKR responses, as few of these children were able to provide behavioral responses. The average difference in motion coherence threshold was 0.94% (95% CI −3.45–1.57, t_{14} = −0.80, P = 0.44) and the single measures intraclass correlation was 0.85 (95% CI = 0.62–0.95, $P < 0.001$, Fig. 3). The threshold results between the first and second session of testing for children who were part of the CHYLD study cohort (n = 4) were not significantly different from those of the noncohort children (n = 11, 1.37 ± 4.05 vs. −1.78 ± 4.58, t_{13} = 1.21, P = 0.25).

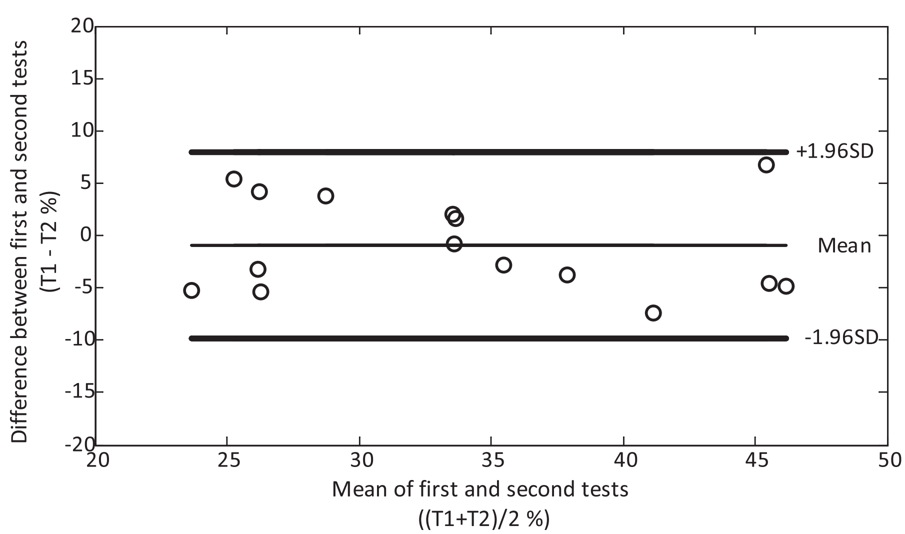

Figure 3. Bland-Altman plot of test–retest reliability for 2-year-old children who completed motion coherence threshold measurements on two separate days. T1, threshold from the first test; T2, threshold from the second test.

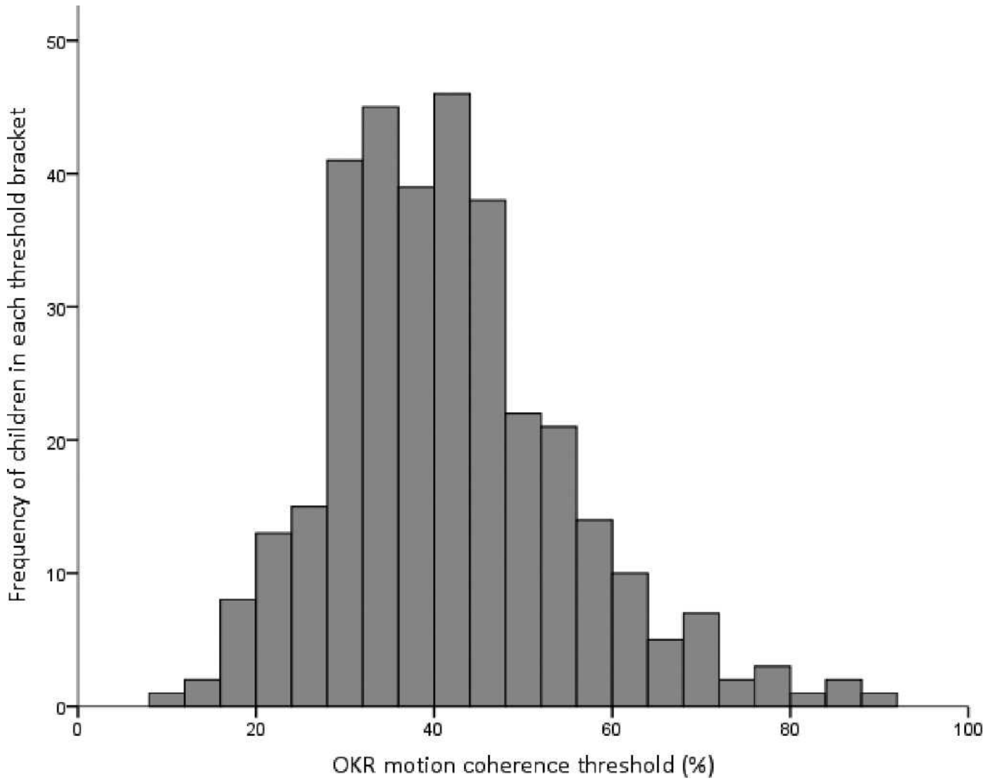

FIGURE 4. The distribution of OKR motion coherence thresholds for 336 2-year-old children.

Motion Coherence Threshold Estimates in Children

The average OKR motion coherence threshold was 41.7 ± 13.5% and the distribution was skewed to the right ($P < 0.005$ for comparison with a normal distribution, Fig. 4). Although the range of thresholds was large (9.0%–88.2%), 75% (252/336) of the children had thresholds ranging from 28% to 56% (the central region of the distribution shown in Fig. 4). The mean and standard deviation excluding children with abnormal findings for visual acuity, an inability to complete stereo testing, strabismus, and significant manifest refractive error (outside the expected norms listed in the Table) were very similar to the mean and standard deviation for the cohort as a whole at 41.6 ± 13.8% ($n = 210$). The examination of individual psychometric functions showed that confidence intervals were large due to the relatively small number of trials, but that the functions were reasonably monotonic indicating that the proportion of directional OKR responses scaled with coherence (Fig. 5).

The Relationships Among Different Measures of Visual Function in Children

Mean Cardiff card binocular visual acuity was 0.05 ± 0.15 logMAR. Mean stereoacuity was 2.52 ± 0.20 log sec-of-arc using the LANG I & II stereo test and 2.46 ± 0.24 log sec-of-arc using the Frisby stereo test. Motion coherence thresholds were correlated positively with stereoacuity measured with the LANG I & II (Spearman's $\rho = 0.28$, $P < 0.001$) and the Frisby ($\rho = 0.18$, $P = 0.013$) stereo tests, but were not correlated significantly with visual acuity ($\rho = 0.11$, $P = 0.065$). When the results for children with abnormal findings for visual acuity, strabismus, and significant manifest refractive error (outside the expected norms listed in the Table) were excluded, the relationship between OKR motion coherence and measures of stereopsis became slightly stronger (LANG I & II, $\rho = 0.34$, $P < 0.001$; Frisby, $\rho = 0.21$, $P = 0.012$). Visual acuity measured using the Cardiff cards correlated with stereoacuity measured with the LANG I & II ($\rho = 0.30$, $P < 0.001$) and Frisby ($\rho = 0.19$, $P = 0.02$) stereo tests. The results of the two stereo tests (LANG I & II and Frisby) also were correlated positively ($\rho = 0.18$, $P = 0.009$).

Motion Coherence Thresholds in Adults

Motion coherence thresholds for OKR responses and behavioral responses were obtained for all 10 adults. The average OKR motion coherence threshold was 3.3 ± 1.2% (range, 1.7–5.6%) and was significantly lower than that based on behavioral data (5.8 ± 1.6%; range, 3.2–9.0%; $t_9 = 9.2$, $P < 0.001$). However, the two measurements were correlated strongly (single measures intraclass correlation = 0.81, 95% CI = 0.41–0.95, $P = 0.001$).

DISCUSSION

Evidence that global motion perception may be a sensitive measure of neurologic and visual cortex development[1,3,5] motivated us to develop and validate a technique for assessing global motion perception in 2-year-old children. We found that video recordings of the optokinetic reflex in response to RDK stimuli with varying levels of coherence allowed for motion coherence thresholds to be calculated by fitting a psychometric function to the proportion of "correct" OKRs for each coherence level. This technique had high repeatability and test–retest reliability. Importantly, measurements were possible for over 90% of the 2-year-old children who took part in this study. This rate of successful measurements compared

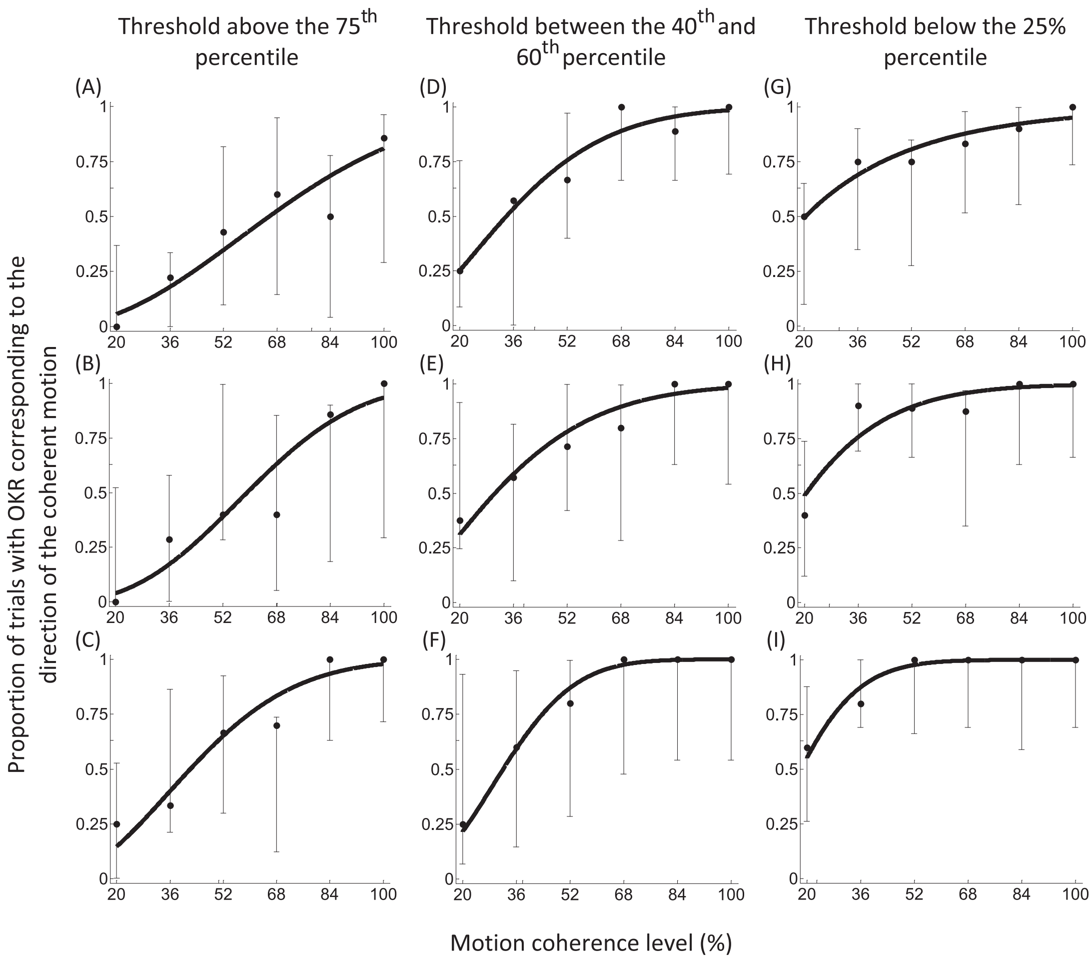

FIGURE 5. Examples of psychometric functions for 2-year-old children with associated 95% CIs for proportions. The *vertical axis* expresses the proportion of trials for which OKR was observed to be in the same direction as the stimulus. (**A–C**) Three examples of children whose thresholds fell above the 75th percentile (high thresholds). (**D–F**) Three examples of children whose thresholds were between the 40th and 60th percentile (moderate thresholds). (**G–H**) Three examples of children whose thresholds fell below the 25th percentile (low thresholds).

favorably to clinical tests of visual function performed on the same children. We cannot rule out an order effect as motion coherence thresholds were measured before clinical testing. However, across all tests, the success rates did not correspond to the preferred testing sequence. For example, stereopsis assessment was less successful than acuity assessment despite occurring earlier in the testing sequence. Only 8.5% of children were able to provide behavioral responses when viewing RDKs. This is in agreement with previous work indicating that reliable behavioral responses generally are not obtainable from children less than 3 to 4 years of age,[45–49] and highlights the importance of using objective measures with young children. We found no obvious differences in age or visual performance between children who could and could not provide behavioral responses.

A comparison between the motion coherence thresholds measured in our study and those measured in previous studies shows a gradual improvement in global motion perception over the first 7 years of life, although thresholds do not reach adult levels (Fig. 6). While this developmental trend is consistent across studies, absolute thresholds vary. For children 1 to 3 months of age, the mean threshold was 60% coherence for studies using preferential looking[30,32] and 30% for those using OKR-based measures.[30,51] Thresholds were more stable on average for 3- to 7-year-old children, with preferential looking[9] and behavioral[34–36,64] techniques providing mean thresholds of 30% coherence. OKR techniques have not been used for this age group. Finally, studies that also included adult observers produced mean adult thresholds of 20% coherence for preferential looking paradigms,[9,30,32] 10% for OKR-based methods,[30,51] and 10% for behavioral responses.[34–36,64] However, as is evident from the variability in Figure 6, these comparisons should be interpreted with caution. In particular, the stimulus parameters and threshold criteria (i.e., whether thresholds reflect 50%, 63%, or 75% correct) differ across studies, which may lead to variations in absolute threshold (see Appendix for further details). For example, it recently has been shown that relatively small changes in dot speed can significantly affect global motion perception in older children.[35] With this in mind, a comparison between child and adult thresholds for an identical stimulus may be more informative, as this gives an indication of how far along the developmental continuum or how "adult-like" children's thresholds are. We found that the mean adult threshold was more than 12 times lower than the mean for our specific cohort of 2-year-old children using the OKR technique. Even the children at the lower end of the distribution did not reach adult levels of performance, suggesting that development of global motion perception was incomplete in our cohort of 2-year-olds. This is in agreement with previous work demonstrating considerable differences between adults and children for the same psychophysical global motion task.[30,34,51]

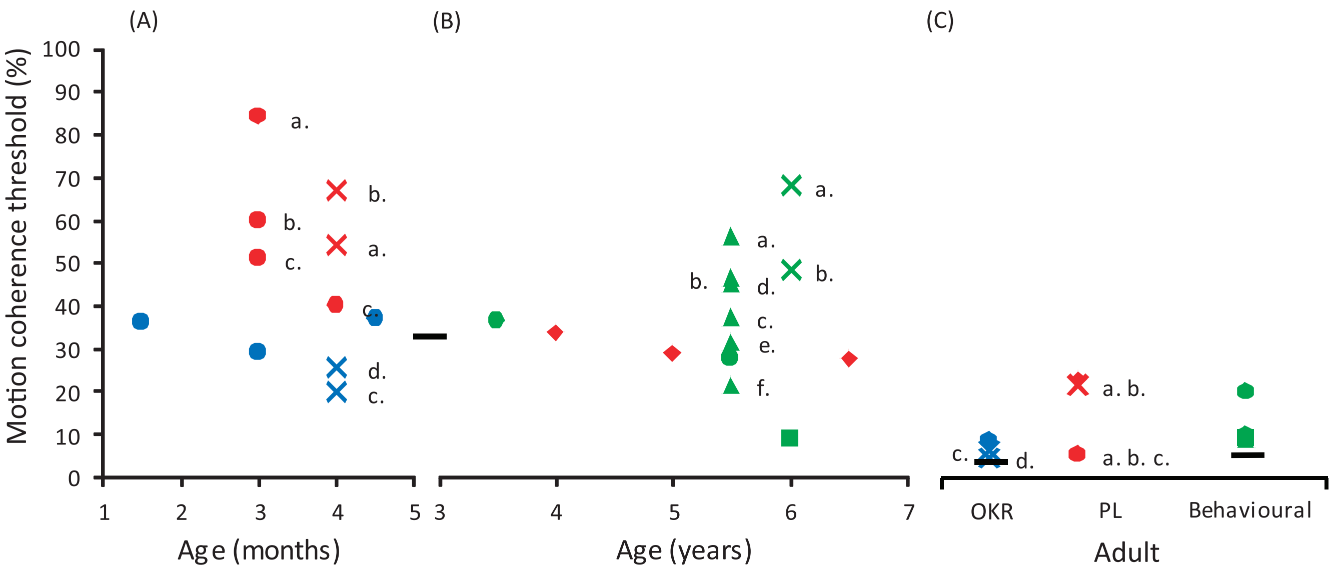

Figure 6. A summary of mean motion coherence thresholds from previous studies of global motion perception in infants and children which used RDKs with dynamic signal and noise dots. (**A**) Results from studies of children aged 1 to 5 months. (**B**) Results from studies of children aged 3 to 7 years. (**C**) Results from studies of that also included adult participants. The *color* of the *markers* denotes the technique used to measure the motion coherence threshold; *blue* = OKR, *red* = preferential looking (PL), and *green* = behavioral responses. The shape of the markers in combination with the color of the marker denotes the study; ● = Wattam-Bell,[32] ● = Bantan and Bertenthal,[51] ✕ = Mason et al.,[30] ■ = Ellemberg et al.,[64] ◆ = Gunn et al.,[9] ✕ = Parrish et al.,[36] ▲ = Hadad et al.,[34] ● and ✕ = Narasimhan and Giaschi.[35] The (**a–f**) labels are to be used in conjunction with Table A1 provided in the Appendix and identify different stimulus parameters used within individual studies. The black horizontal lines represent the average thresholds found in our study for 2-year-old children (OKR) and adults (OKR and behavioral).

Interestingly, the difference we reported for global motion discrimination is considerably larger than that found for the detection of moving dots within a field of static dots, which is only a factor of 3 to 4 times poorer than adult performance by 12 months of age.[37]

The distribution of thresholds we report was relatively wide in comparison with previous studies of global motion perception in children. A number of factors may have contributed to this variability. It is possible that our test had greater variability than other techniques that have been used with children; however our test–retest reliability data indicated that this is unlikely to be the case. Previous studies have used considerably smaller sample sizes, often combined with stringent exclusion criteria. For example children with poor language skills, and children who were uncooperative, fussy, or inattentive have been excluded from prior studies.[9,30,35,36,51,64] This presumably reduced the range of thresholds in these studies. However, our study is not the only one to find high variability in motion coherence thresholds. Hadad et al.[34] also found considerable variability in motion coherence thresholds for children up to 13 years of age. In addition, no previous studies have reported global motion coherence thresholds for 2-year-old children and it is possible that there is considerable variability between children of this age.[59]

While area V5/MT is involved in mediating the OKR in the mature visual system,[21,65–67] it has been suggested that in early infancy the OKR may be driven by subcortical mechanisms.[68–71] Evidence for this includes a nasal/temporal asymmetry under monocular viewing conditions whereby only temporal-to-nasal motion can induce an OKR.[69,71] This asymmetry could be due to a reliance on the nucleus of the optic tract, which contains directional neurons that only respond to nasal-ward motion. The gradual disappearance of monocular OKR asymmetry from the age of 2 months[71,72] presumably is due to the development of cortical pathways that supersede the subcortical mechanism. The majority of studies indicate that the OKN becomes symmetrical before 2-years of age,[69,71,73–76] (however, see the study of Lewis et al.[72]) suggesting that OKN responses involve cortical processing by the age of 2 years. Therefore, our recordings of OKR in 2-year-old children are likely to reflect cortical function. Furthermore, our use of RDKs with limited lifetime dots was designed to target dorsal extrastriate areas, such as V5/MT.[12,16–20,24,77,78]

Interestingly, we found that motion coherence thresholds measured using the OKR were lower than behavioral thresholds in adults whose visual cortex development is complete. One possible explanation is that the OKR reflects activity in the subconscious pathway that directly connects subcortical structures, such as the superior colliculus and pulvinar to V5.[79,80] In fact, it recently was found that the early maturation of area MT likely is to be reliant on retinopulvinar input.[81] An alternative explanation is that OKR is less susceptible to response errors. Whatever the reason for the absolute difference between behavioral and OKR responses in adults, the close correlation between the two measures suggests that they target a common neural mechanism, which is likely to be global motion processing within the extrastriate visual cortex.[13,17,24,82]

Our finding that motion coherence thresholds were correlated positively with stereopsis is consistent with previous work indicating that the development of motion perception and stereopsis are closely related.[83–85] Cells in V5 are exclusively binocular[86,87] and many are sensitive to the retinal disparity signals required for stereopsis.[86,88,89] This suggests that the development of dorsal extrastriate areas, such as V5, influences global motion perception and stereopsis.[90–92] By extension, a deficit in dorsal stream processing would be likely to affect abilities such as visually guided motor control,[2,5,93–95] which rely on stereopsis and motion perception.[96–98] There is a possibility that the correlation between motion coherence thresholds and stereopsis we observed is due to children with more advanced cognitive skills exhibiting superior performance on both tasks. While we cannot rule this out, we note that children who could not complete the stereo testing were not included in the analysis and that the OKR based measure of motion coherence threshold does not require cooperation other than looking at the screen, hence the high success rates in testing.

The narrow range of binocular visual acuities we measured is consistent with previous reports (e.g., the study of Adoh and Woodhouse[59]), and could explain why no relationship was found between binocular visual acuity and motion coherence thresholds. However, it may be the case that motion coherence thresholds are relatively independent of visual acuity. A number of previous studies have demonstrated that motion coherence thresholds are unaffected by optical defocus.[99–101] For example, Trick et al.[100] reported that optically induced blur of 4 diopters (D) or less had no effect on coherence thresholds. Therefore, global motion perception appears to be relatively robust to the spatial frequency content of RDKs when the stimuli are presented at high contrast. This suggests that an assessment of global motion perception could provide information relating to visual cortex development even in the presence of refractive error.

A major obstacle that we faced when assessing 2-year-olds was their limited attention span resulting in only short periods of cooperation. A number of previous studies have used staircase techniques when studying pediatric populations to allow for shorter testing times in an attempt to minimize this issue. However, staircase methods are particularly vulnerable to errors of inattentiveness early in the procedure[102,103] and also require the child's responses to be interpreted on a trial-by-trial basis. This can be challenging, particularly when judging whether children are orienting towards a particular stimulus or exhibiting an OKR, and our pilot observations indicated that a staircase technique was not viable for 2-year-old children. We therefore chose to use a modified method of constant stimuli as this approach is less sensitive to lapses in concentration and allowed for offline analysis, whereby video footage could be examined carefully to ensure that the child was attending to the visual stimulus, and to assess the presence and direction of the OKR. Several other studies of children with developmental disorders have used a similar approach to measure visual function.[104–107]

One disadvantage of our OKR-based technique for measuring global motion perception is that it requires the subjective assessment of OKR eye movements by a trained observer, albeit offline. An automated, objective procedure for quantifying the OKR would be preferable. Such systems have been developed for adult subjects, for example Hyon et al.,[108] but are not currently suitable for young children. With the availability of such a system, the assessment of OKR eye movement could allow for the accurate measurement of a range of visual functions in young children, such as grating acuity and contrast sensitivity.

In summary, the optokinetic reflex can be used to provide reliable and repeatable measures of global motion perception in 2-year old children, which are correlated with stereoacuity and robust to reduced levels of visual acuity. This technique has high testability compared to other age-appropriate pediatric vision tests and may provide a sensitive measure of visual cortex development in young children.

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APPENDIX

The CHYLD Study Team

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Investigative Ophthalmology & Visual Science

Table A1. Summary of the RDK Stimulus Parameters and Response Methods for the Studies Included in Figure 6

Age		Mean Threshold, %	Stimulus (RDK) Parameters						Response Method	Study	Marker
			Speed, deg/sec	Density	Dot Size, deg	Number of Dots	Size of RDK(s), deg x deg	Reversal Rate, msec			
Months	3	84	8		0.32	1056 / RDK	19 x 30 (2)	120	PL	Wattam-Bell 1994[32] a.	red ●
Months	3	60	8		0.32	1056 / RDK	19 x 30 (2)	240	PL	Wattam-Bell 1994[32] b.	red ●
Months	3	51	8		0.32	1056 / RDK	19 x 30 (2)	480	PL	Wattam-Bell 1994[32] c.	red ●
Months	4	40	8		0.32	1056 / RDK	19 x 30 (2)	480	PL	Wattam-Bell 1994[32] c.	red ●
Months	1.5	36	7.4	10%	0.068 x 0.088		22 x 19		OKR	Banton 1996[51]	blue ●
Months	3	29	7.4	10%	0.068 x 0.088		22 x 19		OKR	Banton 1996[51]	blue ●
Months	4.5	37	7.4	10%	0.068 x 0.088		22 x 19		OKR	Banton 1996[51]	blue ●
Months	4	53.9	9.27	2.46 dot/deg	0.26	1056 / RDK	26 x 16.5 (2)	250	PL	Mason 2003[30] a.	red ✖
Months	4	66.8	9.27	2.46 dot/deg	0.26	1056 / RDK	26 x 16.5 (2)	500	PL	Mason 2003[30] b.	red ✖
Months	4	19.8	9.27	2.46 dot/deg	0.26	2112	33 x 33		OKR	Mason 2003[30] c.	blue ✖
Months	4	25.6	9.27	2.46 dot/deg	0.26	528	9 x 33		OKR	Mason 2003[30] d.	blue ✖
Years	6	9	18	0.75 dots/deg	0.083	300	20 x 20		Behavioral	Ellemberg 2002[64]	green ■
Years	4	34.2	6	4 dots/deg				240	PL	Gunn 2002[9]	red ◆
Years	5	29.5	6	4 dots/deg				240	PL	Gunn 2002[9]	red ◆
Years	6.5	28	6	4 dots/deg				240	PL	Gunn 2002[9]	red ◆
Years	3.5	37	1.2	32 dots/deg²			12.8 x 9.6		Behavioral	Parrish 2005[36]	green ●
Years	5.5	28	1.2	32 dots/deg²			12.8 x 9.6		Behavioral	Parrish 2005[36]	green ●
Years	6	69	4	0.75 dots/deg	0.5 x 0.5	300	17.5 x 17.5		Behavioral	Hadad 2011[34] a.	green ✖
Years	6	49	18	0.75 dots/deg	0.5 x 0.5	300	17.5 x 17.5		Behavioral	Hadad 2011[34] b.	green ✖
Years	5.5	57	1	1 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] a.	green ▲
Years	5.5	47	1	15 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] b.	green ▲
Years	5.5	38	1	30 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] c.	green ▲
Years	5.5	46	4	1 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] d.	green ▲
Years	5.5	32	4	15 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] e.	green ▲
Years	5.5	22	4	30 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35] f.	green ▲
Adults		6	8		0.32	1056 / RDK	19 x 30 (2)	120 to 480	PL	Wattam-Bell 1994[32] a. b. c.	red ●
Adults		11	7.4	10%	0.068 x 0.088		22 x 19		OKR	Banton 1996[51]	blue ●
Adults		9	18	0.75 dots/deg	0.083	300	20 x 20		Behavioral	Ellemberg 2002[64]	green ■
Adults		23.5	6	4 dots/deg				240	PL	Gunn 2002[9]	red ◆
Adults		22.4	9.27	2.46 dot/deg	0.26	1056 / RDK	26 x 16.5 (2)	250 and 500	PL	Mason 2003[30] a. b.	red ✖
Adults		8.8	9.27	2.46 dot/deg	0.26	2112	33 x 33		OKR	Mason 2003[30] c.	blue ✖
Adults		7	9.27	2.46 dot/deg	0.26	528	9 x 33		OKR	Mason 2003[30] d.	blue ✖
Adults		20	1.2	32 dots/deg²			12.8 x 9.6		Behavioral	Parrish 2005[36]	green ●
Adults		10	4 and 18	0.75 dots/deg	0.5 x 0.5	300	17.5 x 17.5		Behavioral	Hadad 2011[34]	green ✖
Adults		9	1 and 4	1 – 30 dot/deg²	0.14		7.65 x 5.75		Behavioral	Narasimhan 2012[35]	green ▲

Blank cells indicate that the information was not provided in the original report.