

Reach Kinematics During Binocular Viewing in 7- to 12-Year-Old Children With Strabismus

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Received: September 17, 2021

Accepted: November 24, 2021

Published: December 22, 2021

Citation: Kelly KR, Hunter J Jr, Norouzi DM, et al. Reach kinematics during binocular viewing in 7- to 12-year-old children with strabismus. *Invest Ophthalmol Vis Sci.* 2021;62(15):21. <https://doi.org/10.1167/iov.62.15.21>

PURPOSE. Eye-hand coordination is essential for normal development and learning. Discordant binocular experience from childhood strabismus results in sensory and ocular motor impairments that can affect eye-hand coordination. We assessed reach kinematics during visually guided reaching in children treated for strabismus compared with controls.

METHODS. Thirty-six children aged 7 to 12 years diagnosed with esotropia, a form of strabismus, and a group of 35 age-similar control children were enrolled. Reach movements during visually guided reaching were recorded using the LEAP Motion Controller. While viewing binocularly, children reached out and touched a small dot that appeared randomly in one of four locations ($\pm 5^\circ$ or $\pm 10^\circ$). Kinematic measures were reach reaction time, total reach duration, peak velocity, acceleration duration, and deceleration duration. Touch accuracy and factors associated with impaired reach kinematics were evaluated.

RESULTS. Strabismic children had longer total reach duration (545 ± 60 ms vs. 504 ± 43 ms; $P = 0.002$), had longer deceleration duration (343 ± 54 ms vs. 312 ± 45 ms; $P = 0.010$), and were less accurate ($93\% \pm 6\%$ vs. $96\% \pm 5\%$, $P = 0.007$) than controls. No differences were found for reach reaction time, peak velocity, or acceleration duration (all P s ≥ 0.197). Binocular dysfunction was more related to slow reaching than amblyopic eye visual acuity.

CONCLUSIONS. Strabismus affects visually guided reaching in children, with slower reaching in the final approach and reduced endpoint accuracy. Binocular dysfunction was predictive of slow reaching. Unlike strabismic adults who show longer acceleration duration, longer deceleration in the final approach in strabismic children indicates a difference in control that could be due to reduced ability to use visual feedback.

Keywords: visuomotor development, strabismus, binocular dysfunction, eye-hand coordination, visual development

Strabismus is a common pediatric eye condition that affects 2% to 4% of children and results in discordant binocular experience.^{1,2} Esotropia is a form of strabismus with a nasalward eye turn that can result in a constellation of vision deficits, including amblyopia, binocular dysfunction, and ocular motor deficits that persist even after the eyes have been aligned with glasses or surgery.³⁻⁸ Because esotropia emerges during a critical period of brain development and the effects persist throughout childhood, it has the potential to interfere with other developing systems that rely on vision, such as the motor system.

Coordination between eye and hand movements is essential for efficient object manipulation. Interacting with objects in three-dimensional space requires depth percep-

tion cues in order to localize the object, plan the movements, and guide the arm toward the object of interest.^{9,10} Normal binocular vision during childhood provides important sensory input for optimal development of eye-hand coordination.¹¹⁻¹³ Therefore, discordant binocular experience early in life can significantly affect the maturation of eye-hand coordination. Strabismic and amblyopic children have impaired fine motor skills that require eye-hand coordination, such as placing coins into a box, threading beads on a string, and transferring test answers to a multiple-choice form.¹⁴⁻¹⁸ We recently reported fine motor deficits in esotropic and anisometropic children on a standardized test of motor ability, the Movement Assessment Battery for Children 2.¹⁶ Poor performance was

associated with binocular dysfunction (reduced or nil stereoacuity and interocular suppression), regardless of whether amblyopia was present.¹⁶ Therefore, the extent of visuomotor deficits appears to be more closely associated with binocular dysfunction than with the severity of visual acuity deficit, indicating that normal stereoacuity and fusion are essential to optimal task performance during childhood.^{14,16,17,19}

Reaching is completed in two stages—an acceleration stage that reflects feedforward control (i.e., motor planning) and a deceleration phase that reflects online feedback control.²⁰ Assessing reach kinematics during fine motor tasks can provide information on these two stages and on developmental changes that occur over time. Typically developing children 5 years of age use visual information for planning reaching movements but do not rely on visual feedback to make online corrections, while children 7 years of age begin to use visual feedback to adjust limb trajectory during the movement.^{21,22} Young amblyopic children aged 4 to 8 years with strabismus or anisometropia have prolonged reach in the final approach when reaching to grasp during binocular viewing, related to binocular dysfunction.^{11,23} However, it is unknown whether the more simple task of reaching to touch is also affected.

Here, we evaluated reach kinematics in older children aged 7 to 12 years with a history of esotropic strabismus as they performed a simple reach-to-touch task that required children to touch a dot on the screen with both eyes open. Our goal was to determine the extent to which strabismus affects the maturation of visuomotor control in older children. Further, we aim to explore factors associated with any reach kinematic deficits, such as amblyopia and binocular dysfunction typical of strabismus. Because children are just learning to use visual feedback for online corrections at 7 years of age and may not yet have adapted or formed a compensatory strategy, we hypothesized that strabismic children will be slower than controls in the deceleration phase. Further, we predict that slow reaching will be associated with binocular dysfunction. These data will not only aid in the understanding of how motor skills develop and how they are disrupted by abnormal visual experience but may also help guide interventions to ameliorate or prevent eye–hand coordination impairments in children with esotropia.

METHODS

Participants

Strabismic children aged 7 to 12 years diagnosed with esotropia (herein called strabismic) were diagnosed and referred to the Retina Foundation by pediatric ophthalmologists in the Dallas–Fort Worth area. Strabismic children were initially diagnosed with esotropia but aligned with surgery or spectacle correction to within 12 prism diopters of orthotropia near the time of the test visit. Children with combined mechanism (i.e., strabismus + anisometropia) were included in the strabismus group. Age-similar control children with age-normal visual acuity and stereoacuity and no history of vision disorders were also enrolled. All children were tested with their habitual spectacle correction, which was confirmed by medical record review. No child enrolled in the study was born preterm (<37 weeks gestational age) or had coexisting ocular or systemic disease, congenital infections/malformations, or (neuro)developmental delays. Piloting showed that children with arm lengths (shoulder

to fingertip) less than 50 cm could not comfortably reach the dot on the screen and thus were not enrolled. Medical records were obtained from referring ophthalmologists to extract diagnosis, current alignment, and prior treatment plan. English was the primary language for all children.

Ethics

The research protocol observed the tenets of the Declaration of Helsinki, was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center, and conformed to the requirements of the US Health Insurance Portability and Privacy Act. Informed consent was obtained from a parent or legal guardian, and assent was obtained from children ≥ 10 years of age prior to testing and after explanation of the study.

Procedure

Vision Assessment. Prior to visually guided reaching, all children completed a vision assessment that included the following:

1. Crowded monocular visual acuity with the electronic Early Treatment of Diabetic Retinopathy Study (e-ETDRS) protocol^{24,25} to provide logMAR best-corrected visual acuity (BCVA). Amblyopia was defined as an interocular difference in visual acuity ≥ 0.2 logMAR, with BCVA in the fellow eye ≤ 0.1 logMAR (20/25 or better).
2. Stereoacuity with the Randot Preschool Stereoacuity and Stereo Butterfly Tests,²⁶ converted to log arcsec (ranging from 1.3 to 3.3 log arcsec). Nil (no measurable) stereoacuity was arbitrarily assigned a value of 4 log arcsec.
3. Extent of suppression scotoma using the Worth four-dot fusion test at seven different distances, measured as the farthest distance that four dots are reported, converted to size of suppression scotoma in log degrees.^{27,28}
4. Depth of suppression with a computerized dichoptic eye chart that determines the nonpreferred eye/preferred eye contrast ratio (i.e., balance point) at which the child can overcome suppression and report letters presented to each eye with equal likelihood (Contrast Balance Index [CBI]).^{5,29}

Visually Guided Reaching

Testing took place in a well-lit room and children wore their habitual optical correction during testing if required. Testing was completed with both eyes open and with the child's self-reported dominant hand. Each child was seated at a table with their head stabilized using a forehead/chin rest. We used a previously established visually guided reaching protocol^{30,31} to examine kinematic strategies used by strabismic children to plan and execute reaching. Reach kinematic measures were recorded with the Leap Motion Controller system (LMC, software version 4.0; Leap Motion, Inc., San Francisco, CA, USA), a three-dimensional (3D) motion capture system that records upper limb movements using two cameras and three infrared LEDs. The LMC was placed 10 cm in front of the initial hand position. The initial position of the hand was standardized by having the child use their index finger and thumb to hold a stick affixed to the table at body midline, 5 cm away from the eyes (Fig. 1). Viewing distance of the display monitor was 35 cm.

Prior to testing, hand calibration was completed by having the child first hold onto the stick and then reach



FIGURE 1. Experimental setup. Children held onto a stick placed 5 cm in front of them and, with both eyes open, fixated a cross displayed on a computer monitor at a viewing distance of 35 cm. Once the cross disappeared, a small white dot appeared on the left or right displaced 5 or 10 degrees from fixation. The child was instructed to reach out and touch the dot as quickly and accurately as possible and then return to the stick. The LMC recorded hand movements and was placed 10 cm from the hand's initial starting position.

out with their index finger to touch a 0.3° white dot that appeared sequentially from left to right on the black screen in five different horizontal positions (-10° , -5° , 0° , $+5^\circ$, $+10^\circ$). For visually guided reaching, the child was instructed to fixate a white cross (1.4°) with a red dot in the middle that appeared in the center of the screen. Once the cross disappeared, a 0.3° white dot appeared randomly at one of four locations horizontally displaced ($\pm 5^\circ$ or $\pm 10^\circ$ from fixation). The child was instructed to let go of the stick and reach out and touch the dot with the tip of their index finger as quickly and accurately as possible. As a measure of touch accuracy for each trial, an experimenter observed and recorded whether the child's finger covered the dot (touched) or whether the dot was visible when the child was touching the screen (missed). A total of 40 trials were completed per child, with the first 4 trials counting as practice trials (36 experimental trials). Test time was approximately 15 minutes. Saccades during visually guided reaching were simultaneously recorded with a 500-Hz high-speed video binocular eye tracker (EyeLink 1000; SR Research, Ontario, Canada), but saccades data are not reported in this article.

Data Processing

Reach kinematic data were collected for each trial with the LMC and recorded with a custom Java application using the LMC Software Development Kit (Core Assets 4.1.1). Because the task involved reaching and touching with the index finger, LMC position data from the index finger were extracted and analyzed using a custom MATLAB script (MathWorks, Inc., Natick, MA, USA) that followed previously established signal-processing techniques.^{12,32} Briefly, data were first fitted using a cubic spline function and resampled at 50 Hz using the MATLAB function `pchip`. Next, a Hampel filter was used to remove outliers, and a low-pass second-order Butterworth filter with a cutoff frequency of 10 Hz was then applied. Instantaneous velocity was obtained

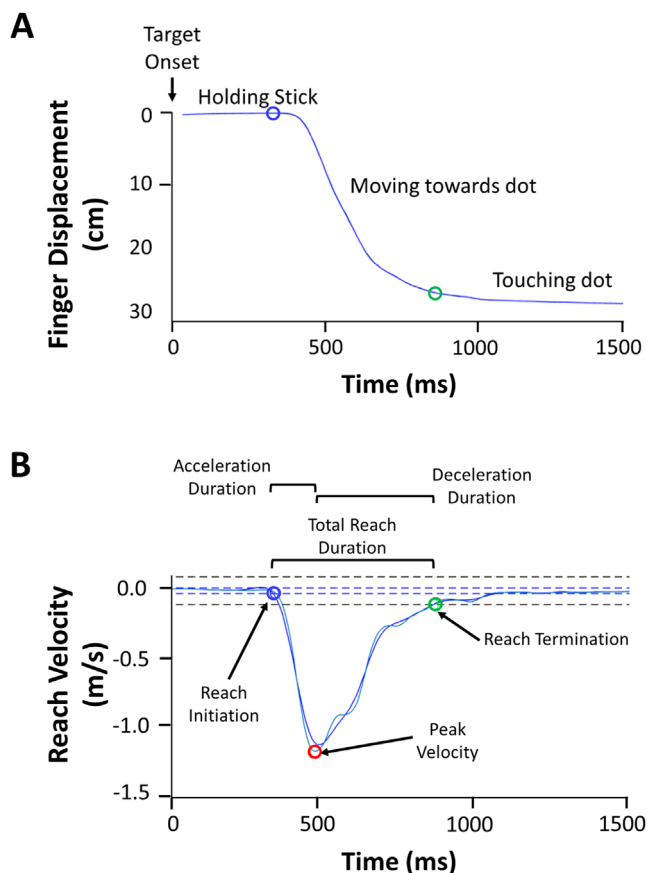


FIGURE 2. Data from a typical reaching trial. **(A)** Position trajectory of the index finger (cm). At the beginning of the trial, the child holds a stick, and then the target white dot appears on the screen (time point 0 ms) and the child reaches out to touch the dot. **(B)** Velocity trajectory of the index finger (m/s). Reach kinematic measures identified based on velocity thresholds (dotted lines) of the index finger. Light blue line is raw LMC data, and dark blue line is resampled, filtered LMC data. Blue circle, reach initiation; red circle, peak velocity; green circle, reach termination.

using a two-point differentiation method, and the velocity data were filtered using a low-pass second-order Butterworth filter with a cutoff frequency of 6 Hz. All position and velocity trajectories were visually inspected and screened for missing frames or artifacts based on previously established criteria.^{12,32} Children with fewer than 14 useable trials (at least 7 useable trials per side, left/right) were excluded from further analysis (4 control, 10 strabismic).

The custom MATLAB script was used to identify two kinematic events: reach initiation (defined as velocity exceeding 20 mm/s) and reach termination (defined as velocity falling below 100 mm/s). These criteria are consistent with previous literature measuring reach kinematics.^{32,33} These events were used to calculate the following kinematic outcome measures (Fig. 2):

1. *Reach reaction time* (ms): the interval between onset of the dot and reach initiation
2. *Total reach duration* (ms): the interval between reach initiation and reach termination
3. *Peak velocity* (m/s): the maximum (i.e., peak) velocity attained during the reach

TABLE 1. Group Characteristics

Characteristic	Strabismic (n = 36)	Control (n = 35)
Sex: female, n (%)	22 (61)	19 (54)
Age, mean ± SD (range), y	9.6 ± 1.7 (7.1 to 12.7)	9.7 ± 1.9 (7.0 to 12.9)
Arm length, mean ± SD (range), cm	57 ± 5 (50 to 70)	58 ± 5 (51 to 68)
Prior eye alignment surgery: yes, n (%) 17 (47) NA		
AE* BCVA, mean ± SD, logMAR	0.2 ± 0.3	0.0 ± 0.1
Snellen equivalent	20/32 ± 3 lines	20/20 ± 1 line
Range	-0.1 to 1.1	-0.1 to 0.1
FE† BCVA, mean ± SD, (range), logMAR	0.0 ± 0.1	0.0 ± 0.1
Snellen equivalent	20/20 ± 1 line	20/20 ± 1 line
Range	-0.1 to 0.1	-0.1 to 0.1
Stereoacuity, mean ± SD (range), log arcsec	3.5 ± 0.9 (1.6 to 4)	1.6 ± 0.1 (1.3 to 1.8)
Extent of suppression, mean ± SD (range), log deg	0.3 ± 0.5 (-0.2 to 1.2)	-0.2 ± 0.0 (-0.2 to -0.2)
Depth of suppression, mean ± SD (range), CBI	5.0 ± 3.9 (0.8 to 10.0)	NA

AE, amblyopic eye; FE, fellow eye; NA, not applicable.

* For nonamblyopic children, either the previously amblyopic eye or the right eye (if the child was never amblyopic) is listed for AE BCVA. For normal control children, the right eye is listed for AE BCVA.

† For children who were never amblyopic and control children, the left eye is listed for FE BCVA.

4. *Acceleration duration* (ms): the interval between reach initiation and peak velocity
5. *Deceleration duration* (ms): the interval between peak velocity and reach termination

Statistical Analyses

Primary analyses. Our primary goal was to determine the impact of strabismus on reach kinematics during visually guided reaching. We used independent *t*-tests to compare strabismic children to control children on each of the reach kinematic measures (reach reaction time, total reach duration, peak velocity, acceleration duration, deceleration duration) and touch accuracy.

Secondary analyses. To determine factors related to reach kinematics, we compared clinical and sensory factors among the strabismic group to controls using independent *t*-tests for prior surgery (yes, no), amblyopia present (yes, no), stereoacuity measurable (present, nil), extent of suppression (Worth four-dot; bifoveal/macular, -0.15 to 0.45 log deg; peripheral/none, 0.60 to 1.2 log deg), and depth of suppression (CBI; no suppression, ≤2; suppression, >2). For data that were not normally distributed according to the Shapiro-Wilk test of normality, Mann-Whitney *U* tests were performed. All tests were corrected for multiple comparisons, and *P* values were adjusted using Holm’s sequential Bonferroni procedure, which corrects for type I error as effectively as the traditional Bonferroni method while retaining more statistical power.³⁴ Effect size was also calculated using Cohen’s *d*. Multiple regression analyses using stepwise selection were conducted to determine the contribution of sensory factors assessed by common clinical tests (amblyopic eye BCVA, stereoacuity, extent of suppression) to reach kinematics.

RESULTS

Data from 36 strabismic children (female = 22; age, mean ± SD = 9.6 ± 1.7 years) and 35 control children (female = 19; 9.7 ± 1.9 years) were included in the analysis. Children with

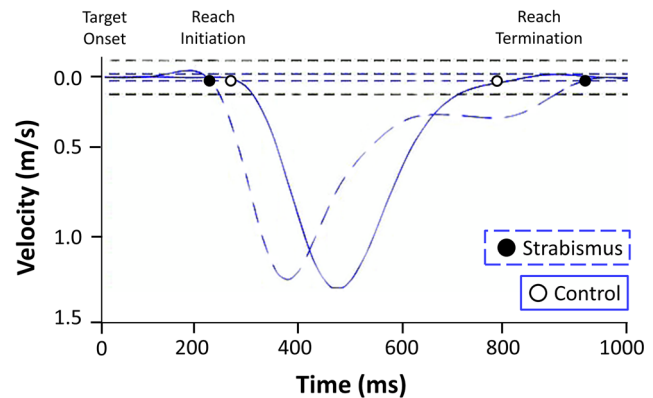


FIGURE 3. Examples of one visually guided reaching trial for a child with strabismus (dashed curve, solid circle) and a control child (solid curve, open circle). The child with strabismus had a longer reach duration than the control child, slowing down (i.e., constant velocity at terminal deceleration), which indicates a more cautious approach.

strabismus did not differ from controls in age (*P* = 0.90) or arm length (*P* = 0.23). Descriptive statistics for clinical and sensory information are provided in Table 1.

Strabismic children did not differ from controls on reach reaction time (strabismus, 355 ± 89 ms vs. control, 351 ± 81 ms; *U* = 627, *P* = 0.972, *d* = 0.05) or peak velocity (strabismus, 1.31 ± 0.20 m/s vs. control, 1.31 ± 0.14 m/s; *t*₆₉ = 0.10, *P* = 0.921, *d* = 0.02). However, strabismic children had longer total reach duration than controls (strabismus, 545 ± 60 ms vs. control, 504 ± 43 ms; *t*₆₉ = 3.23, *P* = 0.002, *d* = 0.77). While not different from controls for acceleration duration (strabismus, 199 ± 24 ms vs. control, 192 ± 19 ms; *t*₆₉ = 1.30, *P* = 0.199, *d* = 0.31), strabismic children had longer deceleration duration than controls (strabismus, 343 ± 54 ms vs. control, 312 ± 45 ms; *t*₆₉ = 2.64, *P* = 0.010, *d* = 0.63) (see Fig. 3 for individual example trials and Fig. 4 for group means). Further, strabismic children had lower touch accuracy than controls (93% ± 6% vs. 96% ± 4%, *U* = 426, *P* = 0.017, *d* = 0.6).

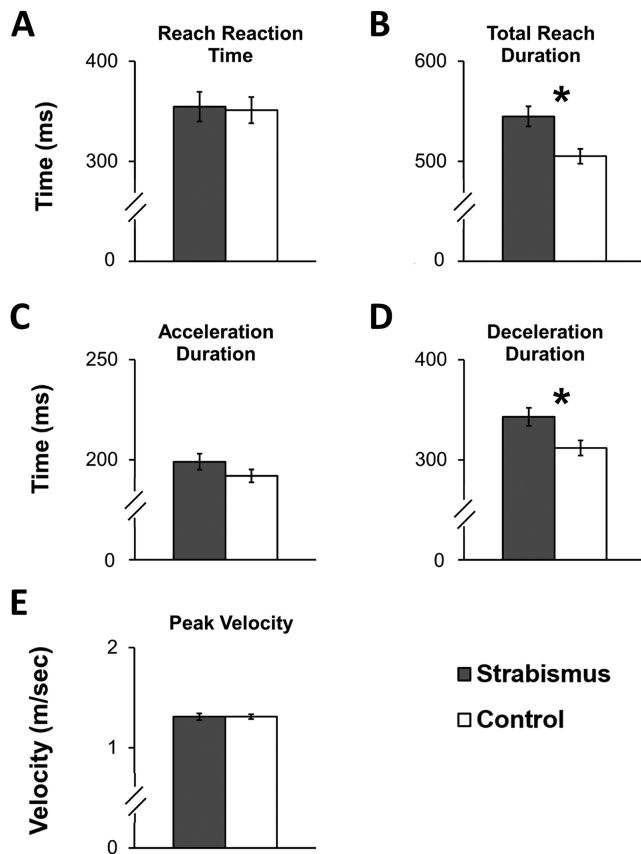


FIGURE 4. Mean reach kinematic measures for strabismic children (dark gray) compared with controls (white). Strabismic children were similar to controls for reach reaction time (A), acceleration duration (C), and peak velocity (E) but had significantly longer total reach duration (B) and deceleration duration (D). Errors bars: ± 1 SE. * $P < 0.05$.

Factors Associated With Reaching Kinematics

We further probed why children with strabismus had longer total reach duration and longer deceleration duration by evaluating clinical and sensory factors. For each factor, we also examined the percentage of the total reach duration that was spent in the deceleration phase (deceleration duration/total reach duration $\times 100$) and touch accuracy.

In general, prior surgery, the presence of amblyopia, nil stereoacuity, and marked suppression (by extent and depth) were all associated with impaired reach kinematics compared to controls, whereas no prior surgery, no amblyopia, measurable stereoacuity, and minimal suppression were not (see Table 2).

Multiple regression analyses were also used to test if sensory factors (amblyopic eye BCVA, stereoacuity, extent of suppression scotoma [Worth four-dot]) significantly predicted total reach duration and deceleration duration. For each model, the variance inflation factor (VIF) was < 1.2 , indicating that the risk of multicollinearity was low.

Total reach duration. Stereoacuity was the only significant predictor for total reach duration, accounting for 16.3% of the variance ($R^2 = 0.163$, $F_{1, 34} = 6.61$, $\beta = 0.40$, $P = 0.015$). The regression estimate was positive, indicating that those with worse stereoacuity had longer total reach duration. Amblyopic eye BCVA and extent of suppression were not significant predictors of total reach duration.

Deceleration duration. Extent of suppression was the only significant predictor for deceleration duration, accounting for 17.2% of the variance ($R^2 = 0.172$, $F_{1, 34} = 7.06$, $\beta = 0.42$, $P = 0.012$). The regression estimate was positive, indicating that those with a larger suppression scotoma had longer deceleration duration. Amblyopic eye BCVA and stereoacuity were not significant predictors of deceleration duration.

DISCUSSION

Slower reaching in strabismic children diagnosed with esotropia, especially in the deceleration phase, is consistent with other studies of amblyopic children and adults who have prolonged reach in the final approach of the more complex task of grasping. Children in our study did not have to shape their hands in preparation for grasping, and thus less planning may be involved, which may have an effect on duration of the reach. Further, because there is less planning involved in reaching to touch than reaching to grasp, errors in our task come at less of a cost (i.e., colliding with/dropping object). Yet, even in this simple reach-to-touch task, deficits in reaching time and accuracy were still present.

Longer deceleration in the final approach may indicate impaired quality or use of visual feedback for motor control, supported by our finding of lower touch accuracy.³⁵ Spatial distortions and positional uncertainty are present in strabismus^{36–38} and could affect the sensorimotor transformation during visually guided reaching. Further adding to the reduced efficiency of the use of visual feedback could be the ocular motor deficits typical of strabismus, including fixation instability, and abnormal saccade initiation and execution.^{4,6,8} Temporal eye-hand coordination during visually guided reaching in amblyopic adults with strabismus and anisometropia is associated with increased corrective saccades, a compensatory strategy to maintain reach precision and accuracy,^{39,40} particularly among adults with nil stereoacuity. Our preliminary saccade data show that strabismic children ($n = 10$) have longer saccade onset latency than controls ($n = 10$) during visually guided reaching (unpublished data). However, saccades did not differ from controls once the eyes started moving; that is, saccade amplitude, peak velocity, temporal eye-hand coordination (time between saccade initiation and reach initiation), and frequency of corrective saccades were similar to controls. This is unlike strabismic adults who show normal saccade latency but more reach-related corrective saccades during binocular viewing, suggesting a compensatory change in strategy that develops with age. Alternatively, children may be making corrective secondary movements during the reach to be more accurate, indicating a problem with motor planning rather than use of visual feedback. Unfortunately, we were unable to determine if corrective movements to the dot were made due to the spatial resolution limitations of the LMC. However, our strabismic children were less accurate in touching the dot compared with controls, suggesting inefficient use of visual feedback during online control is a more likely cause of slow reaching in the final approach.

Adults with childhood-onset strabismus exhibit reduced peak acceleration and prolonged acceleration during binocular viewing on a visually guided reaching task while maintaining normal endpoint accuracy and precision.³¹ Lower peak velocity and longer acceleration in the initial approach

TABLE 2. Factors Affecting Reach Kinematics in Strabismic Children Compared to Controls

Factor	n	Total Reach Duration, Mean (SD), ms	Deceleration Duration, Mean (SD), ms	% Time in Deceleration, Mean (SD)*	% Touch Accuracy, Mean (SD)
Control	35	504 (43)	312 (45)	60.9 (4.9)	96.0 (4.3)
Surgery					
Yes	19	561 (69) [†] <i>t</i> ₅₂ = 3.7, <i>P</i> < 0.001, <i>d</i> = 1.0	364 (60) [†] <i>t</i> ₅₂ = 3.6, <i>P</i> < 0.001, <i>d</i> = 1.0	64.3 (4.7) [†] <i>t</i> ₅₂ = 2.5, <i>P</i> = 0.017, <i>d</i> = 0.7	91.7 (6.1) [†] <i>U</i> = 187, <i>P</i> = 0.007, <i>d</i> = 0.9
No	17	527 (44) <i>t</i> ₅₀ = 1.8, <i>P</i> = 0.086, <i>d</i> = 0.5	319 (34) <i>t</i> ₅₀ = 0.60, <i>P</i> = 0.553, <i>d</i> = 0.2	60.0 (3.5) <i>t</i> ₅₀ = 0.67, <i>P</i> = 0.503, <i>d</i> = 0.2	94.5 (4.7) <i>U</i> = 239, <i>P</i> = 0.244, <i>d</i> = 0.4
Amblyopia					
Amblyopic	19	555 (62) [†] <i>t</i> ₅₂ = 3.5, <i>P</i> < 0.001, <i>d</i> = 1.0	352 (57) [†] <i>t</i> ₅₂ = 2.8, <i>P</i> = 0.007, <i>d</i> = 0.8	62.6 (4.8) <i>t</i> ₅₂ = 1.2, <i>P</i> = 0.230, <i>d</i> = 0.3	92.0 (6.3) [†] <i>U</i> = 200, <i>P</i> = 0.015, <i>d</i> = 0.8
Nonamblyopic [‡]	17	533 (58) <i>t</i> ₅₀ = 2.0, <i>P</i> = 0.050, <i>d</i> = 0.6	333 (50) <i>t</i> ₅₀ = 1.6, <i>P</i> = 0.125, <i>d</i> = 0.5	61.9 (4.6) <i>t</i> ₅₀ = 0.7, <i>P</i> = 0.475, <i>d</i> = 0.2	94.1 (4.6) <i>U</i> = 226, <i>P</i> = 0.152, <i>d</i> = 0.4
Stereoacuity					
Nil	26	558 (61) [†] <i>t</i> ₅₉ = 4.0, <i>P</i> < 0.001, <i>d</i> = 1.0	353 (58) [†] <i>t</i> ₅₉ = 3.2, <i>P</i> = 0.002, <i>d</i> = 0.8	62.6 (5.1) <i>t</i> ₅₉ = 1.3, <i>P</i> = 0.204, <i>d</i> = 0.3	92.4 (5.9) [†] <i>U</i> = 285, <i>P</i> = 0.012, <i>d</i> = 0.7
Present	10	511 (45) <i>t</i> ₄₃ = 0.4, <i>P</i> = 0.690, <i>d</i> = 0.1	316 (31) <i>t</i> ₄₃ = 0.3, <i>P</i> = 0.802, <i>d</i> = 0.1	61.6 (3.5) <i>t</i> ₄₃ = 0.4, <i>P</i> = 0.702, <i>d</i> = 0.1	94.7 (4.4) <i>U</i> = 141, <i>P</i> = 0.366, <i>d</i> = 0.3
Extent of suppression					
Peripheral: no fusion	10	592 (54) [†] <i>t</i> ₄₃ = 5.3, <i>P</i> < 0.001, <i>d</i> = 1.9	391 (44) [†] <i>t</i> ₄₃ = 5.0, <i>P</i> < 0.001, <i>d</i> = 1.8	65.9 (3.5) [†] <i>t</i> ₄₃ = 3.0, <i>P</i> = 0.005, <i>d</i> = 1.1	93.4 (4.1) [†] <i>U</i> = 105, <i>P</i> = 0.050, <i>d</i> = 0.6
Bifoveal: macular fusion	26	527 (53) <i>t</i> ₅₉ = 1.8, <i>P</i> = 0.077, <i>d</i> = 0.5	325 (46) <i>t</i> ₅₉ = 1.1, <i>P</i> = 0.282, <i>d</i> = 0.3	60.9 (4.4) <i>t</i> ₅₉ = 0.0, <i>P</i> = 0.992, <i>d</i> = 0.0	92.9 (6.1) [†] <i>U</i> = 321, <i>P</i> = 0.047, <i>d</i> = 0.6
Depth of suppression					
Suppression	18	559 (69) [†] <i>t</i> ₅₁ < 3.6, <i>P</i> < 0.001, <i>d</i> = 1.0	350 (60) [†] <i>t</i> ₅₁ = 2.7, <i>P</i> = 0.010, <i>d</i> = 0.8	61.9 (4.3) <i>t</i> ₅₁ = 0.7, <i>P</i> = 0.474, <i>d</i> = 0.2	91.3 (6.0) [†] <i>U</i> = 165, <i>P</i> = 0.004, <i>d</i> = 1.0
No suppression	11	515 (51) <i>t</i> ₄₄ = 0.7, <i>P</i> = 0.497, <i>d</i> = 0.2	328 (52) <i>t</i> ₄₄ = 1.0, <i>P</i> = 0.317, <i>d</i> = 0.4	63.3 (5.3) <i>t</i> ₄₄ = 1.4, <i>P</i> = 0.184, <i>d</i> = 0.5	95.3 (4.8) <i>U</i> = 172, <i>P</i> = 0.579, <i>d</i> = 0.2

* Percent time of total reach duration spent in the deceleration phase.

† Significantly different than controls.

‡ For nonamblyopic children, the affected eye was either the at-risk or previously amblyopic eye or the right eye (if the child was never amblyopic).

would indicate that their ability to use vision to plan movements is reduced or that the control system adapted a sensorimotor compensatory strategy in order to maintain endpoint accuracy and precision.^{31,35} In typically developing children, developmental changes in reaching strategy occur with age—children 5 years of age use visual information for planning during reaching and grasping but do not rely on visual feedback to make online corrections. In other words, they rely more on their motor plan and do not adjust errors during reaching based on visual feedback. Children start relying on visual feedback to adjust for errors around 7 years of age, when their reach control starts to become more adult-like.^{21,22} During grasping, amblyopic children 5 to 7 years of age take longer in the final approach than controls and rely more on visual feedback to guide movement, whereas children 7 to 9 years take longer to manipulate the object, relying more on tactile feedback.^{11,23} Strabismic children in our study and children with binocular dysfunctions in a previous study¹¹ exhibit endpoint inaccuracies during reaching

and grasping while viewing binocularly. Further, the reach unfolds in a different manner than controls, with a larger proportion of the total reach spent in the deceleration phase. Thus, the switch between longer deceleration in strabismic children and longer acceleration in strabismic adults points to a compensatory strategy that develops over time with experience so that they can be more accurate in their movements.

Slower reaching in strabismic children who had eye alignment surgery does not necessarily point to a motor deficit caused by surgery. Instead, we suggest that the poorer binocular outcomes associated with the type and severity of strabismus that requires surgery may be at fault. Further, there may have been a longer duration of misalignment that occurs in strabismus that requires surgery rather than strabismus that requires only glasses to align the eyes. In our study, children who had surgery in fact had worse stereoacuity than those who did not have surgery, with almost all children who had a history of surgery (18/19) having nil stereoacuity

but only half of those without surgery (8/17) having nil stereoacuity. It is possible that children who had surgery may be performing better compared to prior surgery. Specifically, eye alignment following surgery may influence visuomotor learning such that children become more efficient in using visual feedback as they reach out and manipulate objects. Indeed, there is evidence that motor skills improve following eye alignment surgery for strabismus in children.^{41,42}

Several studies report fine motor deficits in children with amblyopia, such as placing coins into a box, threading beads on a string, and transferring test answers to a multiple-choice form during binocular viewing.^{14–16,18} Other studies show that amblyopia affects reach kinematics during a grasping task; children and adults with amblyopia are slow at planning and executing reaching movements and have inaccurate grasp during binocular viewing.^{11,23,43} During visually guided reaching, adults with amblyopia exhibit reduced peak acceleration and prolonged acceleration during binocular viewing, without affecting accuracy and precision.^{30,31} Thus, amblyopia affects fine motor skills during binocular viewing, even though one eye has normal visual acuity. The issue may be suppression so that the amblyopic eye is causing interference by adding additional noise to the system. Or, children with amblyopia and interocular suppression may not be using their amblyopic eye to perform the task and instead are using their fellow eye. This may point to a fellow eye deficit in performance. Indeed, studies have also shown slower reaching during fellow eye viewing in amblyopic individuals. Further, fellow eye deficits have been reported for other visual functions such as ocular motor function, motion perception, and reading (for a review, see Birch et al.⁴⁴). However, we did not test children monocularly either with their amblyopic eye or their fellow eye, and thus we cannot be sure which eye is contributing to the reaching deficit found in our study.

Although the presence of amblyopia was associated with motor deficits, this is likely due to the correlation with reduced or absent binocular function. In support of this is our finding that binocular dysfunction (reduced stereoacuity, suppression) was predictive of slow reaching, whereas amblyopic eye visual acuity was not. This is consistent with previous studies showing the importance of good binocular vision in fine motor performance.^{11,14,17,19,45–47} Binocular cues provide vital information for judging distance, location, and 3D properties of objects during motor tasks.^{9,48} The use of binocular cues emerges in infancy and continues to mature during childhood.^{49–51} Binocular discordant input from strabismus early in infancy and childhood may thus disrupt the ability to use binocular cues during the development of motor ability.^{23,52} This is further supported by similar performance to controls in strabismic children with better binocularity in our study. Previous research shows better motor performance in those with recovered binocularity^{11,43} and suggests that binocularity contributes to optimum planning and execution of visually guided reaching.

Fine motor impairments may adversely affect a child's life and may cause difficulties when learning in the classroom, especially in earlier grades when children learn counting and vocabulary by manipulating objects. In later grades, children with strabismus and amblyopia take longer to transfer answers to a multiple-choice form,¹⁸ which could affect performance on timed, standardized tests. Evidence shows that motor impairments are associated with low self-esteem and self-perception in amblyopic children.^{53–55} Treating the visual acuity deficits and binocular dysfunction that accom-

pany amblyopia and strabismus may help improve fine motor ability.⁵⁶

Our study had limitations. The LMC system has robust temporal resolution, but some problems with spatial resolution remain. Spatial accuracy error ranges between 2 and 5 cm,³² and thus measures of endpoint accuracy and precision cannot be reliably obtained with the LMC for the small 0.3° (1.8 mm) dot in our study. Nonetheless, we obtained accuracy data by observing whether the dot was touched. Further, the spatial inaccuracy of the LMC makes it difficult to determine if corrective movements to the dot were made; however, we assessed the primary movement, providing an indication of pointing efficiency. This is the endpoint that has been studied previously with strabismic adults and thus allows us to be able to compare to the adult data.³¹ Teasing apart the individual contributions of clinical and sensory factors is challenging as they often coexist with one another (e.g., strabismus, reduced stereoacuity, suppression).⁴ Yet, it is evident from our data that binocular dysfunction typical of strabismus affects eye-hand coordination during visually guided reaching. Last, we were unable to control for experience with motor skills; however, our task was a simple reaching task with which all children will have had experience, regardless of whether they are enrolled in any physical recreational activities. Nonetheless, many of the children in this study participated in physical recreational activities.

CONCLUSIONS

Strabismus affects visually guided reaching in children. Longer total reach duration was due to more time spent in the deceleration phase. Binocular dysfunction was more predictive of slow reaching than severity of amblyopic eye visual acuity. Unlike adults with strabismus who show longer acceleration duration, longer deceleration in the final approach in strabismic children indicates a difference in control that could be due to reduced ability to use visual feedback. Understanding factors associated with eye-hand coordination deficits in strabismus may help guide development of more effective screening and interventions to prevent or ameliorate motor impairments in strabismic children.

Acknowledgments

Supported by the National Eye Institute (EY028224).

Preliminary results were presented at the 2019 and 2020 annual meetings of ARVO.

Disclosure: **K.R. Kelly**, None; **J. Hunter Jr**, None; **D.M. Norouzi**, None; **R.M. Jost**, None; **A.J. White**, None; **C.S. Cheng-Patel**, None; **C.L. Beauchamp**, None; **L.M. Dao**, None; **B.A. Luu**, None; **D. Stager Jr**, None; **J.Y. Tung**, None; **E. Niechwiej-Szwedo**, None

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