Effects of Reduced Acuity and Stereo Acuity on Saccades and Reaching Movements in Adults With Amblyopia and Strabismus

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Purpose. Our previous work has shown that amblyopia disrupts the planning and execution of visually-guided saccadic and reaching movements. We investigated the association between the clinical features of amblyopia and aspects of visuomotor behavior that are disrupted by amblyopia.

Methods. A total of 55 adults with amblyopia (22 anisometropic, 18 strabismic, 15 mixed mechanism), 14 adults with strabismus without amblyopia, and 22 visually-normal control participants completed a visuomotor task while their eye and hand movements were recorded. Univariate and multivariate analyses were performed to assess the association between three clinical predictors of amblyopia (amblyopic eye [AE] acuity, stereo sensitivity, and eye deviation) and seven kinematic outcomes, including saccadic and reach latency, interocular saccadic and reach latency difference, saccadic and reach precision, and PA/W_e ratio (an index of reach control strategy efficacy using online feedback correction).

Results. Amblyopic eye acuity explained 28% of the variance in saccadic latency, and 48% of the variance in mean saccadic latency difference between the amblyopic and fellow eyes (i.e., interocular latency difference). In contrast, for reach latency, AE acuity explained only 10% of the variance. Amblyopic eye acuity was associated with reduced endpoint saccadic (23% of variance) and reach (22% of variance) precision in the amblyopic group. In the strabismus without amblyopia group, stereo sensitivity and eye deviation did not explain any significant variance in saccadic and reach latency or precision. Stereo sensitivity was the best clinical predictor of deficits in reach control strategy, explaining 23% of total variance of PA/W_e ratio in the amblyopic group and 12% of variance in the strabismus without amblyopia group when viewing with the amblyopic/nondominant eye.

Conclusions. Deficits in eye and limb movement initiation (latency) and target localization (precision) were associated with amblyopic acuity deficit, whereas changes in the sensorimotor reach strategy were associated with deficits in stereopsis. Importantly, more than 50% of variance was not explained by the measured clinical features. Our findings suggest that other factors, including higher order visual processing and attention, may have an important role in explaining the kinematic deficits observed in amblyopia.

Keywords: visuomotor, eye-hand coordination, reaching, saccades

Amblyopia is a common neurodevelopmental visual disorder affecting 2% to 4% of people.[1–3] The clinical diagnostic criterion for amblyopia is reduced visual acuity that cannot be corrected immediately by spectacles, which results in an interocular acuity difference of at least 2 lines on a vision chart. Vision provides important sensory input for the performance of eye and upper limb reaching movements. Our group has conducted detailed kinematic studies to characterize the effects of anisometropic and strabismic amblyopia on saccades,[4,5] reach kinematics,[6–8] and eye-hand coordination.[9–11] We found that adults with amblyopia had longer saccadic latency as well as reduced saccadic and reach endpoint precision during amblyopic eye viewing. Significant differences in reach kinematics (lower peak acceleration and a longer acceleration interval) also were evident in all viewing conditions, suggesting that abnormal visual experience can affect the feedforward control of reaching. Importantly, similar patterns of saccadic deficits and changes in reaching behavior were evident in people with anisometropic and strabismic amblyopia.[4–7,9,11]

Although our previous work demonstrated oculomotor and reach movement deficits in amblyopia, the sample size was not large enough to assess whether clinical features, such as visual acuity and stereo acuity, correlate with behavioral outcomes. The purpose of this study was to use a bigger sample to investigate such correlations. To increase the sample size, we added a third group of participants with mixed mechanism amblyopia that have not been reported previously, and

combined their data with those with anisometropic or strabismic amblyopia. Using multiple regression analysis, we investigated the impact of three clinical predictors: amblyopic eye acuity, stereo acuity, and eye deviation, on specific eye and limb kinematic outcomes that have been shown to be significantly affected by amblyopia, including saccadic and reach latency, saccadic and reach endpoint precision, and altered feedforward reach strategy.[4–9,11]

Materials and Methods

Participants

The sample included 55 adults with amblyopia (22 anisometropic, 18 strabismic, 15 mixed mechanism), 14 adults with strabismus without amblyopia, and 22 visually-normal adults. Of these 55 participants, 22 were not reported in our previous studies[4–7,9,11] (15 mixed amblyopia, 4 anisometropic amblyopia, and 2 strabismic amblyopia). All participants were examined by a certified orthoptist. The visual assessment included visual acuity testing using the Early Treatment of Diabetic Retinopathy Study (ETDRS) chart, stereo acuity testing using the Titmus and Randot tests, and eye deviation measurement using the prism cover test. Amblyopia was confirmed based on an interocular visual acuity difference of at least 2 chart lines, with the fellow eye having acuity of 0.1 logMAR or better. Best corrected visual acuity in the amblyopic eye ranged from 0.18 to 2.00 logMAR. Participants with amblyopia were classified as anisometropic when there was a difference in refractive error between the two eyes that was $\geq$1 diopter in spherical or cylindrical power, with or without microtropia (monofixation syndrome) commonly found in anisometropic amblyopia[12] (i.e., <8 prism diopters [PD] eye deviation). Participants with amblyopia were classified as strabismic when there was a manifest eye deviation (>8 PD) and <1 diopter interocular difference in spherical or cylindrical power. Mixed mechanism amblyopia was defined as the presence of eye deviation >8 PD and $\geq$1 diopter interocular difference in spherical or cylindrical power. Detailed clinical characteristics of the participants are provided in Supplementary Table S1. Visual acuity was 0.1 logMAR or better in both eyes in the visually normal participants and the strabismus without amblyopia group. All participants had no known neurologic disorders, and no eye pathology other than amblyopia, strabismus, or ametropia.

The study was approved by the Research Ethics Board at The Hospital for Sick Children and all protocols adhered to the guidelines of the Declaration of Helsinki. Informed consent was obtained from each participant before experimentation.

Apparatus

Detailed descriptions of the apparatus and the experimental protocol can be found in our previous reports.[4–11] Briefly, participants were seated with their head in a chin rest, their arm positioned in a standardized location while facing a computer monitor (Diamond Pro 2070SB; resolution 1600 × 1200 pixels at 85 Hz; NEC-Mitsubishi, Itasca, IL, USA) located 42 cm from the eyes. Eye movements were recorded using a binocular video-based system at 200 Hz (Chronos Vision, Berlin, Germany). Arm kinematics were recorded at 200 Hz using an Optotrak Certus 3020 motion capture system (NDI, Waterloo, Canada). A white fixation cross was presented on a black background at the center of the monitor. When the fixation cross disappeared, a target was presented (white circle subtending 0.25°) randomly at one of 4 locations: ±5° or ±10° along the azimuth at eye level. Participants wore their corrective lenses (if any) and were instructed to look at and reach to touch the target as quickly and accurately as possible. The task was completed in 3 viewing conditions: both eyes open (BE), fellow eye (FE) (dominant eye of the control participants was determined by Dolman's "hole-in-card" test), and amblyopic eye (AE) (nondominant eye of the control participants), which were randomized in blocks among the participants. There were 240 trials in each viewing condition.

Data Analysis

Eye and hand kinematic data were analyzed as described previously.[4–11] Briefly, position data were filtered using a bidirectional low pass second order Butterworth filter (cut-off frequency was 50 Hz for the eye data and 7.5 Hz for the hand data). A custom MATLAB (Mathworks, Natick, MA, USA) script was used to identify movement initiation and termination. Saccadic and reach latency were obtained using velocity criteria. Specifically, the latency of the movement was defined from the onset of the stimulus to when velocity was >20°/s for saccades, and >30 mm/s for reaching movement. The end of the movement also was defined using velocity criteria (<20°/s and 30 mm/s, respectively). All data were inspected visually to ensure that the script correctly identified the onset and offset of movements.

Seven kinematic outcomes were examined: latency (saccadic latency, interocular saccadic latency difference [i.e., the difference in saccadic latency between the amblyopic eye and the fellow eye], reach latency, interocular reach latency difference [i.e., the difference in reach latency between the amblyopic eye and the fellow eye]), saccadic and reach precision (assessed by calculating the standard deviation across the reaching trials in a given experimental condition along the azimuth), and PA/W_e ratio. The PA/W_e was the ratio between the mean reach peak acceleration (PA) toward targets presented at each location and the corresponding effective target width (W_e), where W_e was defined as the endpoint precision of the reach response toward targets presented at each location. According to the motor-output variability theory proposed by Schmidt et al.,[13] higher peak acceleration would be associated with larger endpoint variability; however, typical reach movement times are >500 ms, so online feedback can be used during the deceleration phase to correct errors in the trajectory and reduce endpoint error. Therefore, the ratio of PA to endpoint precision (i.e., W_e) provides an index of the effectiveness of the online feedback correction process. For instance, a high PA/W_e ratio indicates that the person can engage in an effective online correction process because the potential error due to high PA was amended and endpoint precision was high (i.e., low W_e). In contrast, a low PA/W_e ratio indicates that the person either generated a high PA and has a large endpoint error, or generated a low PA to achieve better precision. The PA/W_e ratio analysis extends our previous work by examining the interaction between feedforward and feedback processes during the execution of reaching movements.

Statistical Analysis

All statistical analyses were performed using the SAS 9.2 software package (SAS, Inc., Cary, NC, USA). Preliminary analysis using ANOVA found no statistically significant differences among different etiologies for all seven kinematic outcomes during amblyopic eye viewing. Therefore, etiology was not included as a separate factor in the subsequent regression analyses.

A Spearman correlation analysis was conducted to examine the correlations between the three clinical predictors: AE acuity (logMAR), stereo sensitivity (1/arc sec), and the angle of

Table 1. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Saccadic Latency During Amblyopic Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	30.81	<0.0001	0.28	−470*
Stereo sensitivity (SS)	1,75	16.60	0.0001	0.17	−459
Deviation	1,75	3.61	0.06	0.03	−447
Multivariate analysis					
AE acuity + SS	2,74	16.25	<0.0001	0.29	−469
AE acuity + deviation	2,74	15.44	<0.0001	0.28	−468
SS + deviation	2,74	8.22	0.0006	0.16	−456
AE acuity + SS + deviation	3,73	10.69	<0.0001	0.27	−67

df, degrees of freedom.

* The AIC model with the fewest predictors and lowest AIC.

manifest eye deviation (PD). Because stereo acuity could not be measured in 27 participants with amblyopia who failed the Titmus test, we used stereo sensitivity instead of stereo acuity since nil stereo acuity could be represented easily as zero stereo sensitivity and, thus, be used in quantitative analysis. Consistent with previous literature,[14,15] preliminary analysis showed a strong negative correlation between eye deviation and stereo sensitivity ($r = -0.74$; $P < 0.0001$), and a moderate negative correlation between AE acuity and stereo sensitivity ($r = -0.48$; $P = 0.0002$).

Because of the correlations between the 3 clinical predictors in the main analysis, a univariate analysis was performed first to examine the correlations between the three clinical predictors and the seven kinematic outcomes, which was followed by a multivariate regression that included only those predictors that had P values <0.1. The best-fitting multivariate model was determined by comparing the candidate multivariate models with the respective predictors using the adjusted R^2 values to avoid collinearity, and the Akaike information criterion (AIC) to assess which candidate model provided the best fit to the data. The AIC is calculated based on the likelihood function for each candidate model, and incorporates a penalty for increasing the number of predictors. Theoretically, adding predictors to the model will always improve the model fit (i.e., the likelihood function), but may lead to overfitting. The AIC was developed to provide a measure of the trade-off between goodness of fit (i.e., likelihood function) and the number of predictors. Thus, the candidate model with the lowest AIC reflects the simplest model, that is, a model with the highest likelihood function and the fewest predictors.[16]

To disentangle the effects of visual acuity loss and strabismus on amblyopia, we also conducted a separate regression analysis for the strabismus without amblyopia group (this analysis included the visually normal group, but not the group with amblyopia). The two clinical predictors in this regression model were eye deviation and stereo sensitivity. Our interpretation of the effect size is based on Cohen's recommendation, which suggested that a Pearson correlation of $r = 0.5$ (i.e., $R^2 = 0.25$) is considered a large effect size.[17]

Results

Effects on Movement Initiation (Latency)

Saccadic Latency. Table 1 shows the results from univariate and multivariate analyses for saccadic latency during amblyopic eye viewing. The best fitting model included AE acuity as a single predictor, explaining 28% of the variance ($\beta = 0.061$, $P < 0.0001$).

Table 2. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Interocular Saccadic Latency Difference

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	70.99	<0.0001	0.48	−523
SS	1,75	30.97	0.0001	0.28	−498
Deviation	1,75	14.84	0.0002	0.15	−486
Multivariate analysis					
AE acuity + SS	2,74	37.70	<0.0001	0.49	−524
AE acuity + Deviation	2,74	41.56	<0.0001	0.52	−528*
SS + deviation	2,74	17.56	<0.0001	0.30	−499
AE acuity + SS + deviation	3,73	27.75	<0.0001	0.51	−526

* The AIC model with the fewest predictors and lowest AIC.

Interocular Saccadic Latency Difference (Table 2). The best fitting multivariate model that explained 52% of variance included AE acuity and eye deviation ($\beta_{AEacuity} = 0.059$, $\beta_{deviation} = 0.001$, $P < 0.0001$), with AE acuity alone accounting for 48% of the variance in the univariate analysis.

Reach Latency (Table 3). The best fitting model yielded AE acuity as the single best predictor, but it accounted for only 10% of variance ($\beta = 0.057$, $P = 0.004$).

Interocular Reach Latency Difference (Table 4). The best fitting multivariate model that explained 10% of variance included AE acuity and eye deviation ($\beta_{AEacuity} = 0.024$, $\beta_{deviation} = 0.001$, $P = 0.007$), with AE acuity alone accounting for 8% of the variance in the univariate analysis.

In separate analyses of the strabismus without amblyopia group, stereo sensitivity and eye deviation had no significant effects on saccadic latency (Supplementary Table S2) or reach latency (Supplementary Table S3) during nondominant eye viewing.

Effects on Precision Error

Saccadic Precision (Table 5). The best fitting multivariate model that explained 27% of total variance included AE acuity and eye deviation as predictors ($\beta_{AEacuity} = 0.060$, $\beta_{deviation} = 0.001$, $P < 0.0001$), with AE acuity alone accounting for 23% of the variance in the univariate analysis.

Table 3. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Reach Latency During Amblyopic Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	9.00	0.004	0.10	−384*
SS	1,75	4.80	0.03	0.05	−380
Deviation	1,75	4.16	0.05	0.04	−379
Multivariate analysis					
AE acuity + SS	2,74	4.52	0.014	0.08	−382
AE acuity + Deviation	2,74	5.25	0.007	0.10	−383
SS + deviation	2,74	3.04	0.054	0.05	−379
AE acuity + SS + deviation	3,73	3.47	0.02	0.09	−381

* The AIC model with the fewest predictors and lowest AIC.

Table 4. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on the Interocular Reach Latency Difference

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	7.96	0.006	0.08	−477
SS	1,75	3.48	0.07	0.03	−473
Deviation	1,75	5.28	0.02	0.05	−475
Multivariate analysis					
AE acuity + SS	2,74	3.93	0.024	0.07	−475
AE acuity + deviation	2,74	5.29	0.007	0.10	−478*
SS + deviation	2,74	3.05	0.053	0.05	−474
AE acuity + SS + deviation	3,73	3.47	0.02	0.09	−474

* The AIC model with the fewest predictors and lowest AIC.

Reach Precision (Table 6). Multivariate analysis revealed that the best fitting model that accounted for 35% of total variance included 2 predictors: AE acuity and eye deviation ($\beta_{AEacuity} = 0.060$, $\beta_{deviation} = 0.001$, $P < 0.0001$). Amblyopic eye acuity alone accounted for 22% of the variance in the univariate analysis.

In separate analyses of the strabismus without amblyopia group, stereo sensitivity was a statistically significant predictor of saccadic endpoint precision ($P = 0.012$); however, the total variance accounted for was only 4% (Supplementary Table S4). Stereo sensitivity and eye deviation had no significant effects on reach precision (Supplementary Table S5) during nondominant eye viewing.

Effects on Reach Sensorimotor Control Strategy (PA/W_e Ratio)

Amblyopia Group. Multivariate analysis revealed that the best fitting model included stereo sensitivity and eye deviation as the predictors and accounted for 25% of total variance during amblyopic eye viewing ($\beta_{stereo\ sensitivity} = 27.23$, $\beta_{deviation} = -0.011$, $P < 0.0001$), with stereo sensitivity alone accounting for 23% of the variance in the univariate analysis (Table 7). During binocular viewing, the best fitting model with the lowest AIC value included stereo sensitivity as the sole predictor (10% of total variance; Table 8). During fellow eye viewing, stereo sensitivity was the only significant predictor in the univariate model, accounting for 5% of variance (Table 9). Multivariate analysis was not conducted because there was only one significant predictor in the univariate model.

Table 5. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Saccadic Precision During Amblyopic Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	23.43	<0.0001	0.23	−425
SS	1,75	21.36	<0.0001	0.21	−424
Deviation	1,75	10.97	0.0014	0.12	−414
Multivariate analysis					
AE acuity + SS	2,74	15.15	<0.0001	0.26	−427
AE acuity + deviation	2,74	15.47	<0.0001	0.27	−428*
SS + deviation	2,74	12.02	<0.0001	0.22	−424
AE acuity + SS + deviation	3,73	10.97	<0.0001	0.28	−428

* The AIC model with the fewest predictors and lowest AIC.

Table 6. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Reach Endpoint Precision During Amblyopic Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	21.91	<0.0001	0.22	150
SS	1,75	15.11	0.0002	0.16	155
Deviation	1,75	25.60	<0.0001	0.24	147
Multivariate analysis					
AE acuity + SS	2,74	12.12	<0.0001	0.23	150
AE acuity + deviation	2,74	21.79	<0.0001	0.35	135*
SS + deviation	2,74	15.34	<0.0001	0.27	150
AE acuity + SS + deviation	3,73	14.33	<0.0001	0.37	138

* The AIC model with the fewest predictors and lowest AIC.

Strabismus Without Amblyopia Group (Table 10). Univariate analysis showed that stereo sensitivity was the most significant predictor in all viewing conditions, accounting for 9% to 26% of the variance. Eye deviation also was a significant, albeit less reliable predictor of PA/W_e ratio, explaining less than 10% of the variance.

Discussion

Using a large sample size that included anisometropic, strabismic, and mixed amblyopia, the current study investigated the correlations between three clinical predictors and saccade and reach performance during amblyopic eye viewing. The main findings were: (1) reduced amblyopic eye visual acuity was associated with increased saccadic and reach latency, as well as reduced saccadic and reach precision; (2) reduced stereo acuity was associated with a reduced PA/W_e ratio, an index of effectiveness of online feedback correction process during reaching; (3) the three clinical predictors we investigated explained less than 50% of the variance across all seven kinematic outcomes, suggesting that other factors, including higher order visual processing and attention[18] may have an important role in explaining the kinematic deficits observed in amblyopia.

Table 7. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Reach PA/W_e Ratio During Amblyopic Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	11.45	0.001	0.12	−56
SS	1,75	24.40	<0.0001	0.23	−67
Deviation	1,75	12.50	0.0007	0.13	−57
Multivariate analysis					
AE acuity + SS	2,74	12.28	<0.0001	0.23	−66
AE acuity + deviation	2,74	9.65	0.0002	0.19	−61
SS + deviation	2,74	13.85	<0.0001	0.25	−68*
AE acuity + SS + deviation	3,73	9.27	<0.0001	0.25	−66

* The AIC model with the fewest predictors and lowest AIC.

Table 8. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on Reach PA/W_e Ratio During Binocular Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	0.82	0.367	0.00	−67
SS	1,75	9.86	0.002	0.10	−76*
Deviation	1,75	3.89	0.052	0.04	−70
Multivariate analysis					
SS + deviation	2,74	5.10	0.006	0.10	−74

* The AIC model with the fewest predictors and lowest AIC.

Deficits in Saccadic and Reach Initiation (Latency) Are Associated With Impaired Acuity

We found that amblyopic eye acuity is the single best predictor of saccadic latency when viewing with the amblyopic eye, explaining 28% of the variance in mean saccadic latency, while acuity explained 48% of total variance in interocular latency difference. These findings are consistent with a recent report by McKee et al.,[19] which showed that the interocular visual acuity difference was strongly correlated with the interocular difference in saccadic latency ($r = 0.75$, $r^2 = 0.56$), especially in people with strabismic amblyopia compared to those with anisometropic amblyopia.[19]

Interestingly, although initiation of saccades and reaching movements were triggered by the same visual stimulus, AE acuity explained only approximately 10% of variance in reach latency and interocular reach latency difference. Only a few studies have assessed manual responses in people with amblyopia, and most of them used a manual press response and a centrally presented target.[20–24] Using such a paradigm, Hamasaki and Flynn reported a high correlation (Pearson's $r = 0.82$ [$r^2 = 0.67$]) between visual acuity and the manual response latency.[20] The apparent discrepancy between their findings and ours may be due to target location. Because visual acuity loss is associated with the depth of suppression in amblyopia,[15,25,26] it is perhaps not surprising that manual reaction time to the central target used in the experiments of Hamasaki and Flynn[20] was associated with acuity loss. In contrast, the target we used was presented at 5° and 10° eccentricity, which may explain why acuity accounted for only approximately 10% of variance in reach latency. Taken together, these results indicated that the effects of amblyopia on eye-hand coordination are task-dependent. These task-dependent effects on eye-hand coordination are supported by previous reports in humans and nonhuman primates.[27–30] For example, manual reaction time in response to a peripheral target was significantly faster for a pointing movement than a manual button press response.[30] In addition, concurrent execution of arm movements could influence saccade kinematics, such that saccadic latency is shorter and peak velocity is higher.[28,29]

Table 9. The Effects of AE Acuity, Stereo Sensitivity, and Eye Deviation on PA/W_e Ratio During Fellow Eye Viewing

Factor	df	*F* Value	*P* Value	Adjusted R^2	AIC
Univariate analysis					
AE acuity	1,75	0.03	0.872	0.00	−75
SS	1,75	4.59	0.035	0.05	−79*
Deviation	1,75	1.03	0.313	0.01	−76

* The AIC model with the fewest predictors and lowest AIC.

Table 10. The Effects of Stereo Sensitivity and Eye Deviation on PA/W_e Ratio in the Strabismus Without Amblyopia Group Across Viewing Conditions

Factor	df	*F* Value	P Value	Adjusted R^2	AIC
Binocular					
SS	1,34	13.60	0.0008	0.26	−39*
Deviation	1,34	5.58	0.024	0.12	−32
SS + Deviation	2,33	6.63	0.004	0.24	−27
Dominant eye					
SS	1,34	5.74	0.022	0.12	−16*
Deviation	1,34	4.24	0.047	0.08	−15
SS + Deviation	2,33	2.92	0.068	0.10	−14
Nondominant eye					
SS	1,34	4.29	0.045	0.09	−33*
Deviation	1,34	4.36	0.045	0.09	−33*
SS + deviation	2,33	2.47	0.101	0.08	−31

* The AIC model with the fewest predictors and lowest AIC.

Reduced Saccadic and Reach Endpoint Precision Is Associated With Impaired Acuity

Motor imprecision could arise from spatial distortions and increased positional uncertainty, which have been documented extensively in strabismic[31–34] and anisometropic[35] amblyopia during perceptual tasks that require judging the relative position of targets. Positional uncertainty and perceptual distortions may arise from topographic disarray with suboptimal calibration[36] or from neural undersampling[37] during development. Notably, a significant correlation between visual acuity loss and increased positional uncertainty has been found in adults[38] and children with amblyopia.[39] Our results extended previous work by showing that amblyopic eye acuity is the primary factor associated with decreased saccadic and reach precision, which could be related to increased positional uncertainty. Oculomotor abnormalities that are associated commonly with strabismic amblyopia, such as latent nystagmus[40] and fixation instability,[41] also may contribute to saccadic imprecision by increasing variability in the coding of initial eye position, which is critical for accurate programming of eye movements.

Altered Sensorimotor Control of Reaching Movements Is Associated With Reduced Stereo Sensitivity

Our results showed that among participants with amblyopia, those with reduced stereo sensitivity had the lowest PA/W_e ratio, indicating they have the most difficulty using online control to correct errors during movement execution, a result that is consistent with our previous findings showing that amblyopia alters the reach control strategy.[6–8]

The contribution of binocular vision to the performance of upper limb movements has been studied in adults and children with abnormal vision. Seminal studies by others[42–45] examined the impact of amblyopia on reaching and grasping movements and reported more errors as well as overt corrections during the transport deceleration phase and grasp execution, which led to longer movement durations. In a subset of individuals with residual stereopsis, individual stereo acuity thresholds explained 50% of the variance in the duration of deceleration phase and grip application time.[43] Improved performance on grasping tasks also was found in children who recovered more binocular function following amblyopia treatment.[44] These findings, together with those from the present study, indicate

that the presence of some degree of stereopsis is associated with better reaching performance. Furthermore, several previous studies have shown that the contribution of binocular vision is greater during more challenging tasks that require reaching and grasping objects placed at different distances.[46–48] Therefore, it is likely that stereopsis would explain a larger proportion of variance in the performance of more challenging tasks than that in the current task which involved reaching to targets displayed in the same depth only.

Why did stereo sensitivity have a significant role in the performance of a relatively simple reach-to-touch task that required no manipulation of target objects? One possibility is that it is not stereopsis per se that is critical for the optimal development of sensorimotor control, but rather that stereopsis is strongly associated with another underlying factor/process that is disrupted by decorrelated binocular visual experience during development. In other words, it is plausible that the abnormal binocular interactions in the striate and extrastriate cortex[49,50] have a downstream effect on the development of other cortical areas involved in the optimal control of visually guided movements.[42,43,51]

Optimal control of movement relies on two processes: feedforward control (i.e., movement planning), as well as feedback control, which can involve multiple early and late correction processes during movement execution.[52–54] Feedforward control is an important aspect of optimal sensorimotor control of voluntary movements.[55–58] Numerous studies support the idea that human motor control relies on an internal forward model, which is an internal simulation of the action that can be used to predict the sensory consequences of a motor command (i.e., corollary discharge).[55–62] Importantly, the ability to successfully engage in feedforward control requires a precisely calibrated internal model; that is, the mapping between the sensory input and the motor outflow to control the effector must be accurate and precise. It is conceivable that the visual impairment in amblyopia disrupts the development of the internal model (retinotopic and/or visuomotor maps) through increased sensory noise,[31,34,63–65] and consequently disrupts feedforward control.

If the feedforward control is less effective, the amblyopic system would have to rely on feedback to a greater extent. This type of control is slow and would be demonstrated by multiple corrections in the latter portion of the trajectory, which is consistent with the experimental results from Grant et al.[42] and Melmoth et al.[43] The ability to correct trajectory errors is limited by the delays inherent in sensory signal transduction and processing, as it takes approximately 100 ms for visual feedback to influence an ongoing movement.[66] Therefore, an important adaptation to deal with sensory delays is to reduce the potential errors associated with motor variability, specifically by reducing the potential error associated with high limb acceleration. Our previous studies have shown that adults with amblyopia had significantly reduced peak acceleration and an extended acceleration phase duration, which were evident in all viewing conditions.[6,7] As previously proposed, lower peak acceleration reduces the motor variability that would be associated with a given motor command (signal-dependent noise), and results in lower endpoint variability.[13,67] Therefore, adopting this strategy allows people with amblyopia to achieve normal reach precision, at least under binocular and fellow eye viewing conditions. However, this strategy is not effective when viewing with the amblyopic eye because endpoint errors persist, which indicates that the effectiveness of online correction is reduced. Taken together, results from our study and those from Grant et al.[42] provide complementary evidence that feedforward and feedback control are disrupted by abnormal visual experience in amblyopia.

Other Factors Affecting Saccades and Reaching Movements

Perhaps the most important finding of the current study is that the three clinical predictors—visual acuity, eye deviation, and stereopsis—explained less than 50% of variance in the kinematic outcomes we investigated. Our findings suggested that other factors, including higher order visual processing and attention,[18] also may have an important role in explaining the kinematic deficits observed in amblyopia. This is supported by numerous studies that showed that in addition to visual acuity and stereopsis deficits, people with amblyopia also demonstrate higher-level perceptual deficits, including decrements in global form and motion integration,[68] global contour processing,[69] second-order motion detection,[70,71] and symmetry detection.[72] Deficits on tasks that involve higher-order attentional components, including underestimation in a visual object enumeration task,[73] prolonged attentional blink,[74] and decreased accuracy when tracking single or multiple objects,[75] also are evident. The attentional explanation is appealing because it also may explain why the physiologic deficits in striate/extrastriate cortex were not large enough to account for the behavioral deficits.[76–78] Sustained attentional suppression also could be acting in addition to physiologic deficits in striate/extrastriate cortex to exacerbate the behavioral deficits. Our findings highlighted once again that amblyopia is not merely a simple visual disorder, it is a complex disorder that affects multiple sensory,[79–81] motor,[10,42,45,51] and perceptual[18,82,83] functions that cannot be explained by lower level deficits alone.

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