City Research Online

Citation: Grant, S. & Conway, M. L. (2023). Deficits in reach planning and on-line grasp control in adults with amblyopia. Investigative Ophthalmology and Visual Science, 64(14), 45. doi: 10.1167/iovs.64.14.45

Eye Movements, Strabismus, Amblyopia and Neuro-Ophthalmology

Deficits in Reach Planning and On-Line Grasp Control in Adults With Amblyopia

Simon Grant and Miriam L. Conway

Centre for Applied Vision Research, School of Health & Psychological Sciences, City, University of London, London, United Kingdom

Correspondence: Simon Grant, Centre for Applied Vision Research, School of Health & Psychological Sciences, City, University of London, Northampton Square, London EC1V 0HB, UK;
s.grant@city.ac.uk.

Received: June 21, 2023
Accepted: October 26, 2023
Published: November 30, 2023

Citation: Grant S, Conway ML. Deficits in reach planning and on-line grasp control in adults with amblyopia. *Invest Ophthalmol Vis Sci.* 2023;64(14):45.
https://doi.org/10.1167/iovs.64.14.45

PURPOSE. Adults with amblyopia exhibit impairments when reaching to grasp three-dimensional objects. We examined whether their deficits derive from problems with feedforward planning of these prehension movements or in using visual feedback to control them on-line.

METHODS. Twenty-one adults with mild to severe anisometropic and/or strabismic amblyopia and reduced binocularity participated, along with 21 normally sighted age- and gender-matched controls. Subjects used their preferred hand to reach for, precision grasp, and then lift cylindrical table-top objects (two sizes, two distances) using binocular, dominant eye, or amblyopic/non-sighting eye vision just to plan their movements during a 1-second task preview with vision then occluded so feedback was absent or to plan and execute them (i.e., with visual feedback fully available). Kinematic and error measures of the timing and accuracy of the reach and grasp were quantified by view and feedback and compared by ANOVA.

RESULTS. The amblyopic adults performed generally worse than controls across all three views in both feedback conditions. With vision for planning only, their movement initiation and duration times were significantly increased, as were their initial reach times and error rates, especially when using the amblyopic eye alone, whatever its visual acuity loss. These relative planning deficits were only partially rectified with visual feedback available on-line. Relative grasp planning deficits were less evident in the amblyopia group, who instead produced significantly increased grip times and errors under binocular and amblyopic eye visual feedback conditions, although the subgroup with unmeasurable stereovision also formed wider (inaccurate) grasps across all conditions.

CONCLUSIONS. Adults with amblyopia seem to have problems constructing reliable internal spatial representations for the feedforward planning of prehension, particularly with their affected eye and mainly affecting their reach, with additional deficits in on-line grasp control related to poor binocularity.

Keywords: eye–hand coordination, on-line control, binocular stereovision, visual acuity, strabismus

Amblyopia is a common neurodevelopmental disorder with a global prevalence of around 2%.[1] Key risk factors are a misalignment (strabismus) and/or refractive imbalance (anisometropia) between the two eyes during the first 7 to 8 years of childhood, representing a critical period in the normal experience-dependent maturation of the visual cortex.[2] The main neuropathologies in both amblyopia subtypes, occurring in the primary visual/striate cortex and generally worsening in higher downstream extrastriate visual areas, include weak responses to the affected (e.g., deviating) eye,[3–6] partly mediated by direct suppressive influences from the dominant (fellow/fixing) eye,[7–9] and the loss of corresponding binocular activations.[10,11] Consequently, people with amblyopia characteristically exhibit reductions in visual acuity (VA) and contrast sensitivity in their affected eye and a range of binocular dysfunctions, such as impaired sensorimotor fusion and stereo/depth vision.[2,12] The normal processing of binocular vergence and disparity cues is a prominent feature of dorsal stream extrastriate cortex.[13–15] Indeed, amblyopia has been associated with deficits in several widely accepted dorsal stream functions, such as global motion perception,[16,17] spatial localization,[18–20] attentional engagement,[21–24] and control of eye, limb, and body movements,[25–28] deficits that can sometimes generalize across all three (i.e., binocular, dominant eye, and affected eye) viewing conditions.[12,17,22,23,26,28]

Our interests have been in determining the nature and underlying mechanisms of the deficits in eye–hand coordination skills for reaching, precision grasping, and manipulating objects (i.e., prehension) in people with amblyopia, which, as with impairments in some other fine manual skills,[29–32] seem more related to their subnormal binocularity than monocular VA losses.[33–37] Performance of these goal-directed movements typically involves two fundamental visuomotor transformation stages[38–40] mainly mediated by distinct dorsal extrastriate and parietofrontal cortical networks,[41–44] with additional inputs from ventral stream object perception areas.[45] First the three-dimensional (3D) spatial position of the target object has to be located and fixated, so that its solid 3D size, shape, and material properties can be extracted, these steps being key to the planning (i.e., off-line or feedforward control) of the reach and grasp, respectively. More specifically, determining the egocentric distance of the target is required to decide the optimal velocity and trajectory for transporting the hand toward it, with information about its solid properties being used to decide the optimal hand posture and thumb–finger contact points for securing the grip. When the movements begin, visual feedback derived from continuous monitoring of real-time changes in depth between the moving hand/digits and the goal object is normally used to detect and correct spatial errors in the reach or grasp (i.e., on-line control), leading to improvements in their endpoint accuracy. Evidence obtained from developmentally normal adults suggests that processing of two sources of binocular information, usually compromised in amblyopia, makes an important contribution to proficient performance. Vergence-related distance signals, generated when fixating the target, influence the reach plan, with disparity-related information regarding the 3D properties of the object being incorporated into plans for the grasp and (more critically) also providing the fast and reliable feedback required for on-line control.[46–48]

Indeed, our studies[33,37] and those of others[49–52] have found evidence suggesting that adults with persistent amblyopia of either subtype have deficits in both feedforward and feedback prehension control mechanisms compared to such neurotypical subjects. For one thing, they usually spend relatively more time in the planning stage prior to movement initiation, an effect that, although most consistent when using their amblyopic eye alone, can also occur for binocular and dominant eye viewing, too. Kinematic parameters of the initial reach and grasp thought to reflect the immediate outcomes of these lengthier planning processes are also generally prolonged across all of these three views in amblyopic compared to normal adults. Specifically, they spend selectively more time in the acceleration phase of the reach and in opening their hands to a peak grip when preparing their grasp. These more cautious starts to their movements have been interpreted as attempts, at the planning stage, to partly compensate for uncertainties in visually encoding the 3D properties of the target and in selecting the best motor response for the task at hand.[37,49–51] They also spend extra time applying their grasp after contacting the object, suggesting recourse to another, non-visual adaptation for impaired on-line guidance of the grasp, in which haptic feedback acquired during this immediate post-contact period takes primacy in establishing the reliability of the final grip.[33,37]

These approaches differ notably from those of normal adults operating under various conditions of uncertain prehension planning, such as with monocular viewing[33,52–55] or simulated anisometropia.[48] In these conditions, subjects generally open their grip to a peak aperture earlier in the movement, and they prolong the late deceleration phase of the reach when approaching the target, consistent with spending extra time using visual feedback to try to improve endpoint accuracy. The inferred attempts by amblyopic adults to trade prehension speed for accuracy are, however, only partly successful, as their performance remains slower and more error prone and imprecise (i.e., variable), often across all three views compared to normal subjects, implying inadequacies in on-line control regardless of whether the visual feedback employed for the purpose involves binocular, dominant eye, or affected eye vision.

The current experiments were designed to explicitly test these inferences by directly comparing the speed and accuracy of reaching and grasping performance in amblyopic adults under so-called open- versus closed-loop conditions. That is, vision was available only to plan the upcoming movements and was occluded just before the hand began to move, in contrast to the more everyday situation (as previously studied in the work cited above[33,34,37,49–55]) in which continuous visual feedback from both the hand and the target were available throughout execution of the movement. The logic was that movements performed in the absence of visual feedback would be products of a feedforward mode of control, based on the visuospatial representation of the task and motor response selections (i.e., the internal model) generated at the planning stage; any improvements in performance with full vision (FV) available throughout the movement would reflect the use of visual feedback to correct errors existing at the planning stage. The test involved further direct comparisons with developmentally normal adults behaving under the same conditions, so that we could formally evaluate any *relative* between-group differences in their use of vision for planning only (VPO) and for on-line control with FV available.

These direct tests of our hypotheses are important. The first reason is because we recently applied them to normally sighted adults and found that advantages of binocular over monocular vision for prehension planning were not quite as marked[56] as originally inferred from earlier analyses of FV prehension in similar subjects.[33,37,55] Second, many adults with amblyopia are aware that their visual impairments place limitations on their ability to control their hands and/or other actions when engaging in activities of daily living, to the extent that they self-report employing various strategies, including caution, to help ameliorate their difficulties.[57] These observations show that their movement deficits are cognitively penetrable and may, therefore, arise mainly or solely from problems with constructing reliable internal models for action planning. If so, they may be amenable to instructional training regimes that target off-line motor learning mechanisms for enhancing predictive/feedforward control.[58,59] On the other hand, it could be that their deficits arise primarily from difficulties with rapid processing of visual feedback for on-line action control, with failure to instantiate robust internal world models being a secondary consequence of such impoverished real-time experiences. This possibility aligns most closely with our previous conclusions that the acquisition of neural substrates supporting binocular stereovision in childhood are key to the optimal development of prehension skills.

MATERIALS AND METHODS

Participants and Their Visual Status

Two groups of 21 adult subjects gave informed consent to participate in the experiments, conducted with approval from the Senate Ethical Committee of City, University of London, and followed the tenets of the Declaration of Helsinki. Subjects undertook a series of clinical tests of their visual status, during which they wore any habitual spectacle or contact lens corrections for refractive errors. Corrected binocular, dominant (Dom)/sighting eye, and non-dominant

(ND)/amblyopic eye logMAR VA was measured using standard Bailey–Lovie charts viewed at the conventional distance of 6 meters. Binocular functions were tested at near from measures of suppression (using Bagolini striated glasses), at motor fusion/vergence break points (with a variable prism bar applied base-out and base-in), and at crossed stereoacuity (SA) thresholds (Wirt–Titmus test; Stereo Optical Co. Inc., Chicago, IL, USA), with any ocular deviation assessed by cover test. Table 1 summarizes clinical details related to the amblyopic adults, all of whom were right handed (scoring ≥+70 on the Edinburgh Handedness Inventory).[60] Subjects with anisometropia had a difference in refractive error ≥ 1 D between the two eyes in the same major meridian. Those with strabismic amblyopia had a constant manifest deviation (tropia), with several exhibiting signs of mixed etiology.

As in our previous work,[33,37] the depth of amblyopia present was determined from the interocular difference in VA between the two eyes and ordinally classed as being mild, moderate, or severe for IODs, with values of 0.20 to 0.39, 0.40 to 1.0, and >1.0 logMAR, respectively. The two subjects with the most severe amblyopia (cases 20 and 21) had resided in the United Kingdom for <2 years and had never been treated. The rest had received some patching therapy between the ages of 3 and 8 years, although six other subjects classed as moderately or severely amblyopic recalled being only partially or very poorly compliant with this therapy. Eleven members of the amblyopic cohort appeared to be non-binocular, in that they had complete suppression of their affected eye and no (Nil) motor fusion; and they were classified as stereo Nil, because they failed the Titmus fly at the largest available disparity of 3000 arcsec. All of the other 10 subjects had reduced stereovision, with SA thresholds ≥ 80 arcsec, but seven cases (1, 4, 5, 7–9, 15) who exhibited some preservation of sensory fusion also had normal convergence facilities, as indicated by base-out motor fusion break points ≥ 20 pˆ (prism diopters).

Control subjects had developmentally normal or corrected-to-normal vision. They were selected so as to match the members of the amblyopia group by gender (five males, 16 females), age (range, 18–58 years; mean ± SD, 26.2 ± 9.7) and right-handedness. Twelve had participated in our previous study.[56] Mean ± SD binocular, Dom, and ND eye logMAR VAs were –0.13 ± 0.08, −0.08 ± 0.09, and −0.06 ± 0.09, respectively, with IODs all ≤ 0.12 logMAR. All subjects had normal vergence facilities, with minimum break points at least 20 pˆ base-out and 16 pˆ base-in, and fine-grade SA thresholds of at least 40 arcsec. Unpaired *t*-tests confirmed no significant between-group differences in subject age ($P = 0.30$) or Dom eye VA ($P = 0.14$), but binocular logMAR acuities were slightly better in the control group ($P = 0.037$).

Recording and Evaluating the Subject's Hand Movements

Methods were similar to those of our recent related studies.[37,56] Subjects sat at a small black table gripping a circular (30-mm-diameter) button between the thumb and index finger of their right hand, which served as a fixed start and end position for each movement trial. Small infrared (IR) reflecting spherical markers (7-mm-diameter) were placed on the wrist and on the thumbnail and index-finger nail of this hand. The positions of these, along with a fourth IR marker attached to the goal object in each trial, were recorded by three Proflex (Qualisys AB, Göteborg, Sweden) IR-emitting and IR-detecting cameras located at different positions above the table. The motion capture rate was set at 60 Hz with the cameras calibrated to a spatial accuracy of <0.4 mm before each experiment. Liquid-crystal PLATO Visual Occlusion Spectacles (Translucent Technologies Inc., Toronto, ON, Canada) were used to control the subjects' viewing conditions on each trial. These were large enough to fit comfortably over any spectacles that the subjects habitually wore. The goggle lenses were rendered instantaneously transparent over both eyes or just over the Dom eye or ND/amblyopic eye via electronic signals sent from the PC also controlling the camera system to start the different hand movement trials. On these, participants were instructed to reach for, precision grasp, lift, and place to the right side of the table the single goal object presented by moving as naturally and accurately as possible. Objects were one of two neutral, white cylinders (100-mm high) that offered high-contrast targets against the black table top surface and were readily amenable to precision grasping; one was relatively small and lightweight (23-mm diameter, 32 g), but the other was larger and heavier (46-mm diameter, 128 g). These were placed at one of two locations: at a relatively near (250 mm) distance from the start button along the subject's midline or at a far (400 mm) distance 10° off-midline to the right and closer to the subject's arm's length.

All participants completed a full set of four blocks of 24 trials, each of which was a combination of the three views by two object sizes and two distances, repeated twice. Trial types followed the same pseudorandomized order (specifically, identical view × size × distance combinations never occurred consecutively) within the four different blocks to add some variety to the task and to reduce predictability regarding the next upcoming trial type. In the first two blocks, the signal to move was the sudden opening of the PLATO lenses, and they remained open for 5 seconds while the subjects planned and executed their movements with visual feedback continuously available (i.e., under closed-loop, full-vision conditions). In the last two blocks, vision was available for planning the movements only (i.e., under open-loop, VPO conditions). In the latter, the PLATO lenses opened for a 1-second period to allow sufficient time for the subject to fixate the goal object and plan their movement toward it. The lenses then closed, and this was the signal to move so that the reach and grasp were performed with vision occluded. A few practice trials were given under each view before each experimental condition to ensure that each participants performed according to instructions. Any VPO trials in which the subject false-started during the preview were discarded and rerun at the end of the relevant block. We chose to run FV and VPO trials in separate blocks to minimize the occurrence of altered strategy effects on closed-loop performance reported to occur when the two feedback conditions are systematically interleaved or randomized within a trial block.[61] We also chose to run the two FV and two VPO blocks in that order, rather than counterbalancing them within the groups, to try to equalize any potential short-term learning biases related to the general experimental setup on the subject's VPO performance, as stereo-deficient people can have extra difficulty performing 3D tasks that are unfamiliar.[28]

The recorded hand movement data were initially processed using programs written in MATLAB (MathWorks, Natick, MA, USA). These generated a number of objective measures of the reach and the grasp kinematics, along with

Table 1. Details of Amblyopic Subjects

				Visual Acuities (logMAR)				Binocular Vision		Presenting Rx	
ID	**Sex/Age (y)**	**BO**	**DE**	**AE**	**IOD, Depth**	**Bagolini**	**BO, BI**	**Stereo (arcsec)**	**Deviation**	**Reye**	**Leye**
1	F, 20	−0.16	−0.12	0.10	0.22, mild	Fusion	40, 8	80	None	−2.50	−4.00/+0.25 × 180
2	F, 21	0.02	0.04	0.24	0.20, mild	Fusion	18, 14	200	SOT + accomm	+3.00/−1.00 × 100	+4.00/−1.50 × 100
3	F, 27	−0.16	−0.08	0.16	0.24, mild	R complete	Nil	Nil	Infantile RSOT, now XOT	None	None
4	M, 27	−0.16	−0.16	0.14	0.30, mild	R central	20, 16	800	RSOT microtropia	+2.75	Plano/−0.50 × 10
5	M, 21	0.02	0.02	0.32	0.30, mild	R central	20, 16	200	RSOT microtropia	+1.75/−1.25 × 180	+1.75/−1.25 × 180
6	F, 21	0.06	0.10	0.44	0.34, mild	R complete	Nil	Nil	SOT then XOT	−0.5/−0.25 × 75	−1.25/−0.50 × 73
7	F, 36	−0.08	−0.02	0.36	0.38, mild	Fusion	40, 20	200	None	−1.00/−0.50 × 67	+1.25/−0.5 × 42
8	M, 51	0	0	0.38	0.38, mild	R complete	Nil	Nil	SOT then XOT	+0.5	+0.5
9	F, 19	−0.08	−0.08	0.32	0.40, moderate	Fusion	30, 16	100	None	Plano/−0.25 × 90	−4.25/−1.75 × 90
10	F, 28	−0.06	−0.02	0.40	0.42, moderate	R complete	Nil	Nil	RSOT	+5.25	+3.50
11	F, 26	−0.14	−0.14	0.30	0.44, moderate	L alternate	Nil	Nil	L/ALT-SOT	Plano/−1.75 × 150	−2.75/−1.75 × 30
12	F, 28	−0.04	−0.04	0.42	0.46, moderate	L complete	Nil	Nil	LSOT	Plano	−2.00
13	F, 20	0.02	0.02	0.50	0.48, moderate	R central	12, 4	200"	RSOT Microtropia	−5.00/−0.75 × 20	−5.00/−0.25 × 110
14	F, 31	−0.10	0	0.50	0.50, moderate	R central	18, 4	400	RSOT microtropia	+2.00	Plano
15	F, 18	−0.20	−0.14	0.54	0.68, moderate	Fusion	30, 18	140	None	Plano	+4.25/−0.25 × 20
16	F, 41	0	0	0.74	0.74, moderate	R complete	Nil	Nil	Infantile RSOT	+3.00/−0.25 × 40	+3.00/−0.50 × 30
17	F, 20	−0.12	−0.12	1.00	1.12, severe	R complete	Nil	Nil	RSOT	−12.50/−0.50 × 20	−3.75/−1.25 × 170
18	F, 20	−0.06	−0.08	1.30	1.38, severe	L complete	Nil	Nil	LXOT	+0.50/−0.50 × 180	+4.75/−0.50 × 180
19	M, 57	−0.10	−0.10	1.30	1.40, severe	R complete	Nil	Nil	RXOT	+0.5	+0.75/−0.50 × 170
20	M, 33	−0.26	−0.18	1.26	1.44, severe	L complete	Nil	Nil	LSOT	Plano	+5.50/−0.75 × 140
21	M, 20	0.06	0.06	1.60	1.54, severe	L complete	Nil	Nil	LSOT	None	None

AE, amblyopic eye; BO, binocular; DE, dominant/fellow eye; F, female; IOD, interocular acuity difference; M, male; Bagolini, results of the striated glasses test and region of the amblyopic eye (L, left; R, right) showing suppression (central indicates that both lines were visible but interrupted at the region of fixation in the AE, and complete indicates that only one line was perceived); Con (covergence), Di (divergence), the break points obtained (in prism diopters) in the motor fusion test with the prism placed base-out (BO) and base-in (BI), respectively; stereo, best crossed stereoacuity threshold achieved (in arcsec) on the Wirt–Titmus test. Failure on the fly (at 3000 arcsec) was scored as Nil (unmeasurable). SOT, esotropia; XOT, exotropia; Subject 2 (SOT + accomm) had no tropia with corrected Rx. accomm, accommodative; ALT, alternating, L, R, left or right eye affected.

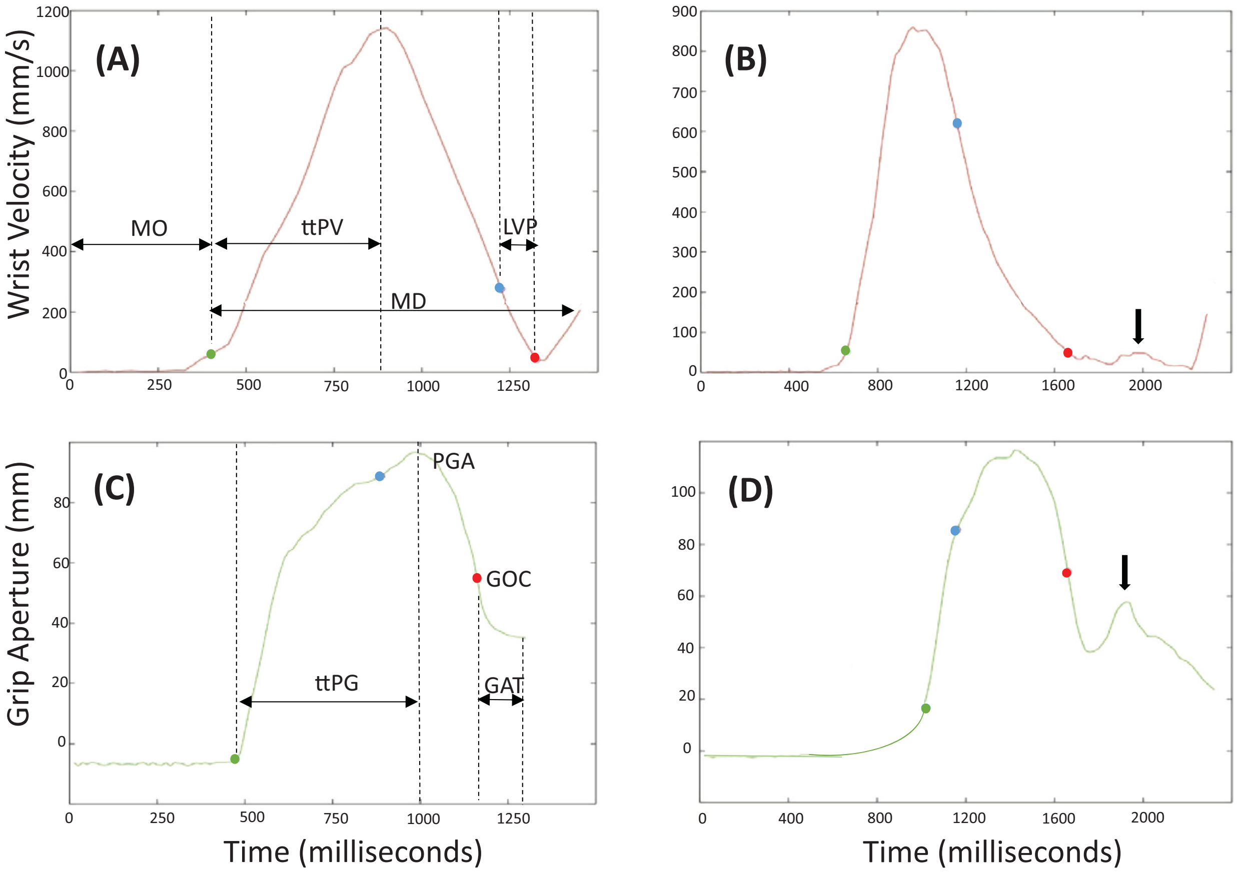

Figure 1. Examples of wrist velocity (**A**, **B**) and grip aperture (**C**, **D**) profiles obtained from correctly executed movements of a control subject (**A**, **C**) in the full vision condition and from an amblyopic subject (**B**, **D**) with VPO. The cue to start moving occurred at time zero in all profiles. *Green circles* indicate movement onset (when the wrist velocity first exceeded 50 m/s); *blue circles* indicate the moment of peak deceleration (PD) of the wrist; *red circles* indicate the moment of initial object contact (when the target was first displaced by ≥1 mm). Panel **A** shows four kinematic parameters derived from the wrist velocity: movement onset (MO) time, time to peak velocity (ttPV), low velocity reach phase (LVP) between PD and object contact, and overall movement duration (MD) between MO and the endpoint (when the target was first displaced by ≥10 mm, indicating that its lift had begun). Panel **C** shows grasp-related kinematic parameters: peak grip aperture (PGA), time to peak grip (ttPG) after MO, grip at object contact (GOC), and grip application time (GAT), between initial contact and the movement endpoint. In panels **B** and **D**, note the prolonged movement onset and duration times; the *arrows* indicate errors or corrections to the movements occurring in the grasp phase after initial object contact. The *arrow* in panel **B** represents a reorientation of the wrist; the *arrow* in panel **D** represents a reapplication of the grip.

depictions of wrist velocity (Figs. 1A, 1B) and its trajectory related to the reach and of changes in the grip aperture (Figs. 1C, 1D) formed by the opposing thumb and index finger between the start and end of each movement. From these, we selected 10 specific dependent measures (see Fig. 1 for illustrations) with which to evaluate the subject's performance on each trial as informed by and defined in our previous work.

Six measures were related to the prehension timings or dynamics. These included the *movement onset* (MO) time between the moments that the PLATO lenses initially opened (FV trials) or closed (VPO trials) and the IR marker on the wrist exceeding a forward velocity of 50 mm/s indicating that the reach had begun. The *movement duration* (MD) between MO and displacement (by ≥10 mm) of the IR marker on the goal object indicated that its lift had begun. These measures are generally accepted parameters of the efficiency/certainty of the movement planning and execution stages, respectively, and previously have been shown to be prolonged in the adult amblyopia compared to control groups under standard (FV) conditions.[33,37] To examine whether different subactions contributed to the expected longer overall MDs, we evaluated two subcomponents of the reach dynamics from the marker on the wrist: the *time to peak velocity* (ttPV), corresponding to its initial acceleration phase, and its *low velocity phase* (LVP), corresponding to the late hand-target approach period (between peak wrist deceleration and initial contact with the object, defined by displacement of the IR marker on its surface by ≥1 mm). Two equivalent (early, late) subcomponents of the grasp were the *time to peak grip* (ttPG), representing the period during which the thumb and finger markers were initially opened to a maximum aperture, and the *grip application time* (GAT), corresponding to the post-contact period spent securing the grasp and applying load forces to the object required to lift it. These four parameters have also been reported to be of longer duration in adult amblyopia compared to control subjects,[33,37,49–51] with the relatively prolonged ttPV and GAT suggested to be compensations for difficulties with visually guided online control during the approach to the goal object (e.g., the LVP).

The other four measures examined aspects of performance accuracy, including error rates. Reaching accuracy was evaluated from the occurrence of forward and/or lateral deviations in the spatial path of the wrist marker before target contact appearing as *mis-reaches* in the hand trajectory. Grasping accuracy was assessed by the width of the *peak grip aperture* (PGA) and the width of the *grip at initial object contact* (GOC), both of which are considered to reflect the reliability with which subjects estimate the size (e.g., width) of the goal object, and by *mis-grasps* appearing as adjustments (reopening and closure) of the digits in the grip aperture profile or as forward/lateral shifts in overall wrist/hand orientation during the object contact phase, indicative of endpoint grasping errors. Adults with amblyopia typically mis-reach and mis-grasp more often than control subjects, problems interpreted as resulting, respectively, from errors in programming hand transport and digit placement on the goal object.[33,37]

Statistical Analyses

Analyses of the dependent kinematic measures were based on the median values obtained under each separate view and feedback condition in the two subject groups; mis-reaching and mis-grasping errors were expressed as the percent of trials in which they occurred by view and feedback in each group. These data were first assessed by repeated-measures analysis of variance (ANOVA) using SPSS Statistics (IBM, Chicago, IL, USA) for the three views × two feedback conditions *within* each subject group. This was to confirm that the control group exhibited the typical binocular advantages over Dom eye viewing with visual feedback available repeatedly observed before in normal adults[36,37,55] and that these advantages were reduced or lost with binocular VPO, as we recently found in a different sample of adult controls.[56] It was also to check that the current sample of amblyopic adults showed the typical prehension deficits previously reported under standard FV conditions.[36,40] The datasets were then assessed by complete (two group × two feedback × three views) ANOVA to identify any main effects of group and any important two- or three-way interactions with feedback and/or view. Main effects of group were examined further by ANOVA to explore any associations with key features of the amblyopic participant's status—that is, with their depth of amblyopia (mild vs. moderate to severe), degree of convergence facility (normal vs. reduced/absent), and stereovision loss (reduced vs. Nil/unmeasurable) as different between-subject factors. Note that it would appear that the subjects falling into these latter categories might also have been classed as binocular versus non-binocular, as all of those with Nil stereo had Nil sensory and motor fusion. However, three of these subjects (10, 16, and 21) reported experiencing depth percepts while viewing 3D movies. We applied the Huynh–Feldt correction when variances in the ANOVA were revealed to be non-spherical and the Bonferroni correction for tests involving more than one pairwise comparison. Significance in these various tests was declared as $P < 0.05$.

Results

Overview

The quantitative data obtained are shown in Tables 2 to 4. Control subjects exhibited the typical binocular advantages over Dom eye viewing in the standard FV condition observed in past studies, but only one (shorter low velocity phases) with VPO.[56] Further in line with previous work, the current amblyopia subjects generally produced slower and less accurate movements than the normal adults with FV available. These deficits were often evident across all three possible views, contributing to the significant main effects of group for eight of the 10 parameters examined (see Tables), with the amblyopic adults also exhibiting fewer binocular FV advantages over their Dom eye, with none at all for grasping performance (Table 4). There were also significant main effects of feedback on nine of the 10 measures due to poorer VPO than FV performance by both subject groups. However, direct comparisons of just their VPO performance (see Figs. 2–4) revealed significant *relative* planning deficits among the amblyopic participants for overall movement onsets and durations and for all three parameters related to their reaching behavior.

Movement Onset and Execution Times

Figure 2 shows the much longer MO and MD times produced by the amblyopia group across all three views with VPO and reveals that this relatively greater caution/hesitancy was particularly striking when subjects used their amblyopic eye. It also shows that both timings were much shorter when on-line visual feedback was either expected after MO (Fig. 2A) or actually present during the movement (Fig. 2B), especially for amblyopic eye viewing, and remained consistently slower than equivalent normal

Table 2. Mean (SEM) Movement Onset and Duration Times

		Control Group			Amblyopia Group		
Parameters	**Feedback Condition**	**Binocular**	**Dom Eye**	**ND Eye**	**Binocular**	**Dom Eye**	**Amb Eye**
Movement onset times (ms)***	Planning only	556 (29)	557 (27)	552 (21)	643 (25)	640 (17)	733 (33)**
	Full vision	483 (16)***	511 (15)	518 (15)	542 (19)***	586 (21)	602 (25)
	Improvement	13%	8%	7%	16%	8%	18%
Movement duration times (ms)**	Planning only	1082 (63)	1116 (66)	1138 (70)	1248 (66)	1271 (65)	1644 (98)***
	Full vision	852 (13)***	954 (49)	975 (21)	963 (42)***	1090 (49)	1151 (55)
	Improvement	21%	15%	14%	23%	14%	30%

Amb, amblyopic; Dom, dominant; ND, non-dominant. Improvement is the percent reduction with visual feedback compared to VPO. Parameters column: main effects of group. Binocular columns: measures showing advantages over the Dom eye. Amb Eye column: measures showing deficits compared to binocular viewing.

$^{**}P < 0.01$.

$^{***}P < 0.001$.

Table 3. Reaching Performance, Mean (SEM)

		Control Group			Amblyopia Group		
Parameters	**Feedback Condition**	**Binocular**	**Dom Eye**	**ND Eye**	**Binocular**	**Dom Eye**	**Amb Eye**
Time to peak velocity (ms)***	Planning only	277 (10)	275 (11)	280 (11)	318 (13)	330 (13)	346 (17)
	Full vision	276 (7)	273 (8)	277 (7)	316 (11)	317 (11)	335 (13)
	Improvement	<1%	<1%	1%	<1%	4%	3%
Low velocity phase (ms)*	Planning only	402 (21)*	466 (30)	462 (32)	516 (44)	506 (34)	707 (70)*
	Full vision	305 (12)***	377 (17)	379 (14)	348 (27)**	411 (33)	434 (30)
	Improvement	24%	19%	18%	33%	19%	39%
Mis-reaches (% trials)**	Planning only	4.8 (1)	7.5 (2)	6.4 (2)	11.3 (2)	12.1 (2)	14.5 (3)
	Full vision	2.5 (1)	4.4 (1)	3.9 (2)	6.9 (1)	10.7 (2)	11.6 (3)
	Improvement	48%	41%	39%	39%	12%	20%

Parameters column: main effects of group. Binocular columns: measures showing advantages over the Dom eye. Amb Eye column: measures showing deficits compared to binocular viewing.

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

Table 4. Grasping Performance, Mean (SEM)

		Control Group			Amblyopia Group		
Parameters	**Feedback Condition**	**Binocular**	**Dom Eye**	**ND Eye**	**Binocular**	**Dom Eye**	**Amb Eye**
Time to peak grip (ms)**	Planning only	521 (28)	515 (20)	525 (31)	583 (29)	603 (30)	708 (39)**
	Full vision	482 (14)	494 (18)	500 (18)	521 (19)	542 (20)	570 (26)**
	Improvement	7%	4%	5%	11%	10%	19%
Grip application time (ms)*	Planning only	211 (17)	223 (16)	222 (24)	227 (17)	235 (22)	289 (32)**
	Full vision	121 (4)*	147 (7)	153 (8)	142 (10)	170 (17)	194 (13)**
	Improvement	42%	34%	31%	37%	28%	33%
Peak grip aperture (mm)	Planning only	88.7 (3)	89.3 (3)	89.5 (3)	92.7 (3)	93.6 (4)	91.8 (4)
	Full vision	72.4 (1)***	77.3 (2)	76.8 (1)	78.2 (2)	80.9 (3)	80.7 (3)
	Improvement	18%	13%	14%	16%	14%	12%
Grip size at contact (mm)	Planning only	54.4 (2)	54.6 (2)	54.2 (2)	55.8 (2)	56.7 (2)	56.5 (2)
	Full vision	44.2 (<1)*	47.1 (<1)	47.1 (<1)	45.3 (<1)	47.5 (1)	46.8 (1)
	Improvement	19%	14%	13%	19%	16%	17%
Mis-grasps (% trials)*	Planning only	40.5 (7)	35.5 (6)	36.5 (6)	50.0 (8)	44.0 (6)	57.6 (8)
	Full vision	4.1 (<1)***	16.2 (2)	19.0 (3)	11.1 (3)	19.5 (4)	34.0 (6)***
	Improvement	90%	54%	48%	78%	56%	41%

Parameters column: main effects of group. Binocular columns: measures showing advantages over the Dom eye. Amb Eye column: measures showing deficits compared to binocular viewing.

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

adult performance. These effects were, together, responsible for significant three-way (group × feedback × view) interactions ($F_{2,82} \geq 4.5$, $P < 0.025$) for both parameters. For example, the average reduction in ND eye MD between VPO and FV conditions was ~160 ms for the control subjects but was ~500 ms in the amblyopia group, as reflected in the relative between-group differences in their mean percent "improvement" between conditions (Table 2). More specifically, mean improvements were similar for binocular movement onsets (13% control vs. 16% amblyopia groups) and durations (21% control vs. 23% amblyopia groups) and for Dom eyes also (i.e., 8% vs. 8% for MO; 15% vs. 14% for MD). But, they were ~2 to 3 times greater for amblyopic compared to normal ND eye viewing (i.e., 7% control vs. 18% amblyopia for MO; 14% control vs. 30% amblyopia for MD). Improvements occurring with binocular visual feedback further resulted in both subject groups acquiring significant benefits over their Dom eyes for both its anticipated (for MO) and actual (for MD) availability in the FV condition (all $P < 0.001$).

Reaching Performance

There were main effects of group on reach timing due to generally slower performance by the amblyopic subjects in both the acceleration and deceleration phases (Table 3). Their slower ttPVs compared to the controls were, moreover, uniquely independent of the view or feedback conditions (Fig. 3A), consistent with strategically altered reach planning by these subjects.[40,48–50] Results for the later, LVP of the reach, however, more closely resembled those for overall movement durations, including the presence of a significant group × feedback × view interaction ($F_{2,82} = 5.1$, $P < 0.025$). Several factors contributed to this. First, the control subjects showed a benefit of binocular over Dom eye vision with feedback available (faster LVPs of ~70 ms, $P < 0.001$), with a smaller binocular advantage ($P < 0.05$) also uniquely present with VPO. Second, the amblyopia subjects' final approach times were significantly slower than the controls with binocular ($P < 0.05$) and, especially, amblyopic eye VPO ($P < 0.001$). But, these improved so much with FV available (by 33% and 39%, respectively) (Table 3) that they were all now

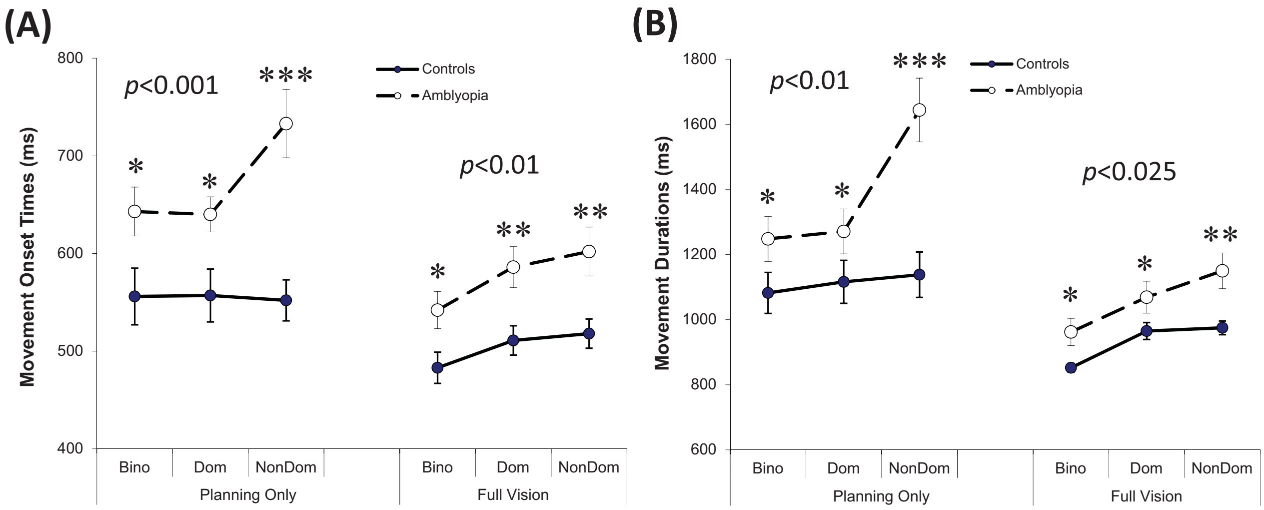

Figure 2. Average movement onset (**A**) and movement duration times (**B**) under each viewing condition with VPO (*left panels*) and full vision (*right panels*) in the control (*filled circles*, *solid lines*) versus the amblyopia (*open circles*, *broken lines*) subject groups. Bino, binocular; Dom, dominant eye; NonDom, non-dominant eye. *Error bars*: SEM. Results of between-group ANOVA for each separate feedback condition are shown. *Asterisks* indicate significantly worse performance by view in each condition in the amblyopic compared to control subjects, derived from univariate ANOVA: *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

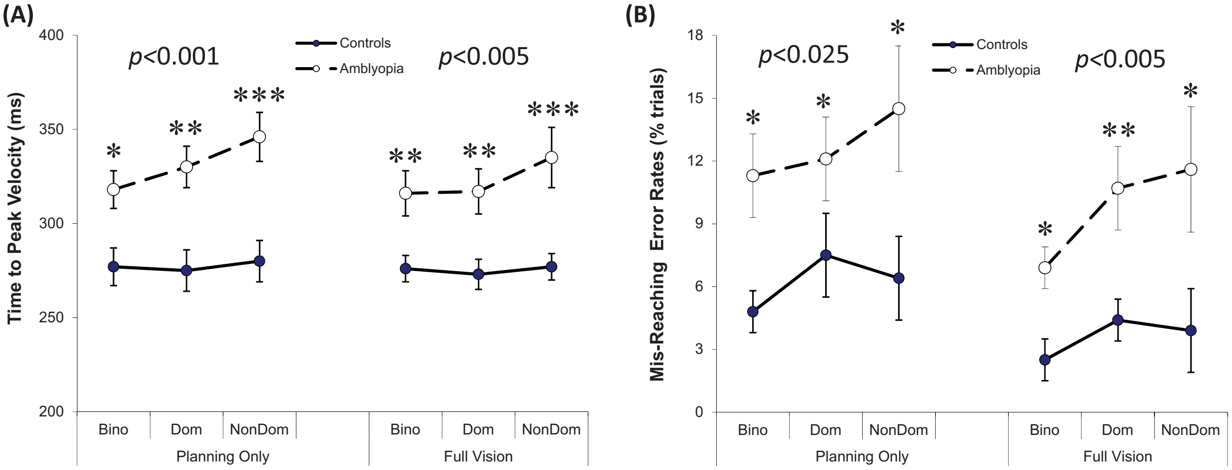

Figure 3. Average initial acceleration times to peak reach velocity (**A**) and mis-reaching error rates by group, view, and feedback conditions (**B**). Conventions are as in Figure 2.

similar to normal ($P > 0.1$), including significantly faster binocular LVPs (of ~60 ms) compared to their Dom eye alone ($P < 0.01$).

There was also a main effect of group on reach accuracy, with the amblyopic subjects committing significantly more mis-reaching errors across all three views in the VPO condition than the control group (Fig. 3B), suggesting poorer target localization during the planning stage. Moreover, this relative planning deficit was not rectified by visual feedback (Fig. 3B), as the improvements in reach accuracy they achieved with FV available were markedly less than normal (by between ~10% and 30%) under each view (Table 3). Figure 3B also indicates that the control group made generally fewer binocular than Dom eye mis-reaching errors, but this apparent advantage did not quite achieve significance ($P = 0.1$), partly due to between-subject variability in their rates of occurrence (Table 3).

Grasping Performance

There were main effects of group on grasp timing (Table 4), with respect to the early phase up to peak grip aperture (ttPG) and to the final grip application time, although these occurred for different reasons. Results for the ttPG broadly resembled those for movement durations, with the amblyopia subjects being significantly more cautious/slower in initially opening their hand than the controls across all three views with VPO ($P < 0.005$), especially with their amblyopic compared to the normal ND eye ($P = 0.001$), but they markedly reduced the relative delays with FV available online ($P < 0.05$). GATs when contacting the objects prior to picking them up showed a novel pattern (Fig. 4A) in which (uniquely for the movement dynamics) the amblyopia group exhibited only a trend toward an overall relative planning deficit ($P > 0.1$), specifically due to their very slow amblyopic eye performance. Instead, their GATs were

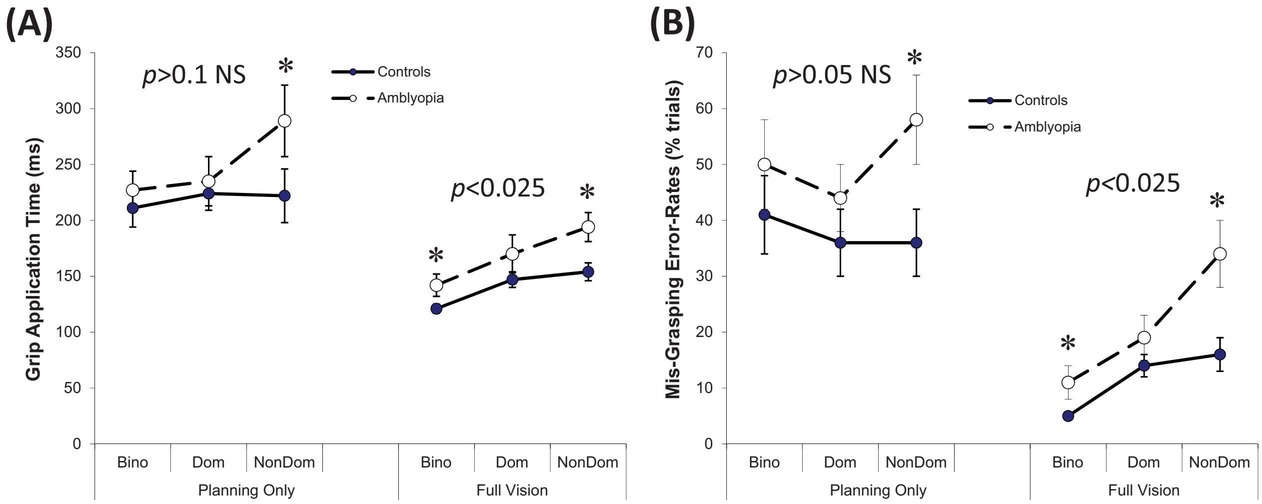

Figure 4. Average grip application times in contact with the objects (**A**) and mis-grasping error rates by group, view, and feedback conditions (**B**). Conventions are as in Figure 2.

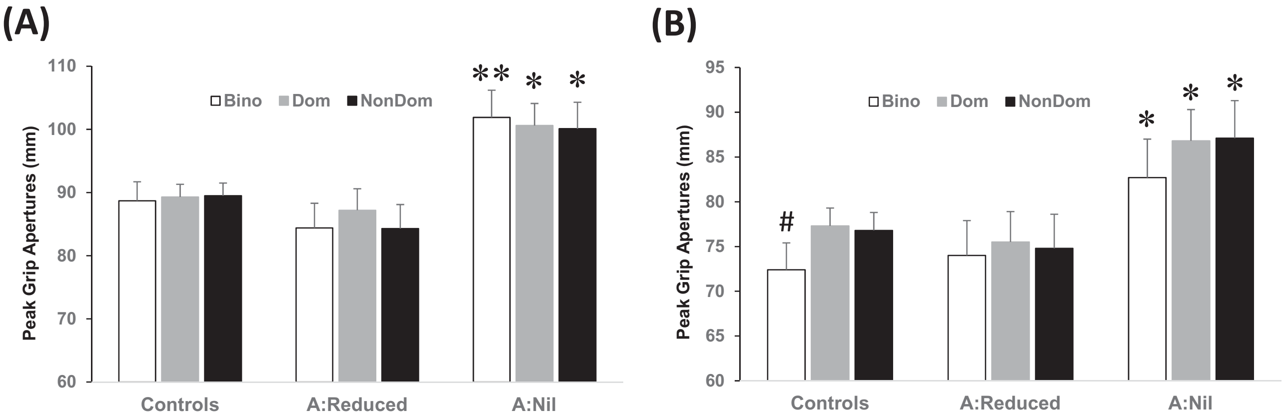

Figure 5. Average peak grip apertures by view in the subgroups of amblyopic subjects exhibiting reduced (A:Reduced) or unmeasurable (A:Nil) stereoacuity with VPO (**A**) and full vision available (**B**). Bino, binocular (*white bars*); Dom, dominant eye (*gray bars*); NonDom, non-dominant eye (*black bars*). *Error bars*: SEM. *Asterisks* indicate significantly worse performance by view in each feedback condition in those with Nil compared to reduced stereoacuity derived from univariate ANOVA: $^*P < 0.05$, $^{**}P < 0.01$. Equivalent data are shown from the normal adult controls, who did not differ from the A:Reduced subgroup, except for the presence of a binocular advantage over Dom eye viewing. $^{\#}P < 0.05$.

significantly prolonged compared to the controls in the FV condition ($P < 0.025$), due to relative deficits in the use of on-line binocular and amblyopic eye vision (both $P < 0.05$) for securing their grip.[36,40] Consistent with this, the normal adults exhibited a typical binocular FV advantage over the Dom eye ($P < 0.05$) for reducing this final period of their grasp, which the amblyopia group did not.

Unlike the reach component, the amblyopia group showed no significant planning deficit for any measure of grasping accuracy that we assessed. Indeed, there were no main effects of group on the width of the grip at peak or initial object contact (Table 4), although control subjects exhibited the usual binocular full vision advantage for enhancing the accuracy of these parameters which the amblyopia group did not share. There was, however, a main effect of group for mis-grasping error rates (Table 4, Fig. 4B). As with their GATs, there was only a trend ($P = 0.1$) toward the amblyopia group committing more VPO errors due to poor performance with their affected eye, with the significant effect ($P = 0.025$) being mainly driven by their higher rates of binocular and amblyopic eye mis-grasping with on-line vision available. This was combined with a lack of a binocular FV advantage for improving grasping accuracy, which was strongly present among the control subjects ($P < 0.001$).

Associations Between Visual and Prehension Deficits in the Amblyopia Group

Spearman's rank correlation analyses established that the degree of visual and stereo acuity loss co-varied among our amblyopic subjects ($r = 0.49$, $P < 0.025$), with each also positively correlated with their existing motor fusion/vergence facility ($r = 0.61$, $P < 0.0025$ and $r = 0.74$, $P < 0.001$, respectively). There were no specific associations between any of these deficits and the apparent cause of their amblyopia.

ANOVA was conducted on each parameter in the VPO condition with each of the three above-listed ordinal features entered as separate between-subgroup factors in the analyses. Given that overall VPO performance was most variable when using the amblyopic eye (refer to the large standard errors evident in Tables 2 to 4), its degree of mild versus moderate-to-severe acuity loss might be expected to correlate with the severity of at least some deficits in movement planning, but it did not, nor were there any rank correlations with their interocular acuity differences or VA class for amblyopic eye performance alone. Instead, the only significant associations found related to their loss of stereovision. First, movement onset times were longer (by 80–90 ms or ~10%–22%) across all three views in the subjects with unmeasurable compared to reduced stereovision ($F_{1,19} = 4.9$, $P < 0.05$). Second, the subgroup with Nil stereoacuity formed much wider grasps (by 12–18 mm or ~10%–20%) across all three views at both peak grip aperture ($F_{1,19} = 5.1$, $P < 0.05$) (see Fig. 5A) and initial object contact ($F_{1,19} = 4.5$, $P < 0.05$; not shown) compared to those in whom some stereovision was preserved.

Further ANOVA by these ordinal features for the full vision condition, again, revealed significant associations only with their degree of stereovision loss. As with VPO, wider grips at peak ($F_{1,19} = 10.9$, $P < 0.005$) (Fig. 5B) and at object contact ($F_{1,19} = 4.6$, $p < 0.05$; not shown) were produced under all three views by the subjects with Nil compared to reduced stereoacuity.

DISCUSSION

Our aim was to determine whether prehension deficits known to be present in adults with persistent amblyopia are mainly products of problems with the feedforward planning or feedback control of their movements. To this end, we compared the reach and grasp performance of normally sighted and amblyopic adults directed at isolated, high-contrast, 3D objects with binocular, dominant, or non-dominant/amblyopic eye vision available to them only during the pre-movement planning stage or during both its planning and execution. There were four major new findings. First, although we anticipated disruptions in amblyopic eye performance with VPO, some of those related to movement timings (e.g., onsets and durations) were particularly marked. Second, we obtained evidence of further generalized relative planning deficits for both reach timing and accuracy affecting all three views. Third, although we found little evidence for comparably generalized grasp planning deficits in the same subjects, aside from slower hand pre-shaping during initial grip formation (i.e., the ttPG), the subgroup with clinically unmeasurable stereovision produced significantly less accurate grips at peak and at endpoint target contact. Finally, relative deficits in binocular and amblyopic eye endpoint grasping performance (increased grip application times and error rates) occurred selectively with full vision available, indicative of impaired on-line control of digit placements on the goal objects.

The notably prolonged movement onset times following amblyopic eye VPO suggests that any feedforward plan, generated by the subjects when viewing the task constraints during the preview, inspired little confidence in their subsequent performance when they knew that vision in this eye would be occluded. Indeed, that performance too was notably slow and cautious, uniquely including significantly increased endpoint grasp times and error rates relative to the matched control view. Amblyopic eye viewing also derived the most benefit for movement initiation when the subjects knew that vision in this eye would be continuously available following the "go" signal and for nearly all aspects of its subsequent execution. These findings further suggest that amblyopic eye vision is, at best, able to support only a rudimentary model for predictive prehension control, as their movements in progress seem to require constant updating via on-line visual feedback. Zhao and Warren[40] argued that such behavior is inconsistent with the generation of any internal model at all but is more likely mediated by a weak off-line strategy based on context-specific spatial memory of the task requirements. Although failure to formulate an adequate motor plan was independent of the severity of the visual acuity loss in the subject's affected eye, our current data do not allow us to identify which of the many attentional and other perceptual deficits specific to amblyopic eye viewing may have contributed to this weakness.

Relative planning deficits in the amblyopic adults were, however, also manifest to a lesser extent by much longer than normal binocular and DOM/fellow eye VPO movement initiation and duration times, indicating that the problem is not exclusive to amblyopic eye viewing. Indeed, as with onset times, movement durations were prolonged in the amblyopia group regardless of view or feedback conditions. A major contributor to these effects was their slow ttPVs, representing the initial acceleration phase of the reach. This slowing effect has been seen before in adult amblyopic subjects under standard FV conditions and is considered an acquired, adaptive strategy designed to enhance subsequent reaching accuracy, which normally sighted adults achieve by slowing the final approach to the target (LVP) for error correction using visual feedback. However, unplanned post hoc repeated-measures ANOVA showed that there were no between-group differences between either of these reach parameters, when expressed as a percentage of their overall movement durations. That is, although the absolute durations of both its acceleration and late deceleration phases were longer in the present group of amblyopic subjects, they exhibited mean proportions of their total (prolonged) execution times equivalent to those of the normal adults (ttPV%, amblyopia 28.5% vs. controls 27.8%, $F_{1,40} = 0.4$, $P > 0.5$; LVP%, amblyopia 40.2% vs. controls 38.9%, $F_{1,40} = 0.9$, $P > 0.25$). Yet their reaching accuracy was poorer than normal across all conditions, with the only marked improvement in error rates (of 39%) occurring with binocular full vision compared to planning only.

Accurate localization of the goal object in 3D space, especially its absolute distance from the viewer, is important for optimal reach planning and execution. Consistent with this, we have previously observed similar effects across all views in amblyopic adults (comparatively slow reaches along with high error rates) under low visibility conditions when such subjects may have had difficulty locating the target against the background environment.[37] We and others[26–28,50–52] have also previously argued that normal binocular vision in childhood provides information essential to developing visuomotor systems underlying the protracted refinement of eye–hand coordination skills, which can partially transfer to action control when using one eye alone. Our experimental setup offered several monocular cues to the distance of the target (e.g., familiar image size, height in scene). But, for the control subjects, an additional binocular metric cue known to enhance normal reaching performance[46,48] should have been provided from signals regarding the degree of convergence achieved when they fixated the object during the VPO preview and with FV available. In fact, the small subgroup of our amblyopic subjects ($n = 7$) (Table 1) with normally preserved convergence facilities made nearly 50% fewer reaching errors than those with reduced or unmeasurable motor fusion in the binocular VPO condition and across all three FV views. Although neither effect achieved statistical significance (both $P < 0.20$), the possibility that mis-reaching in amblyopia may be influenced by deficient access to distance-related vergence information would be worth more specific future attention.

Relative grasp planning deficits were less marked in the amblyopia subjects, but major between-group effects were evident when full vision was available for on-line guidance of the grasp. Accurate judgments of the 3D properties of the goal object (e.g., its size and shape) are considered essential for the optimal thumb and finger placement needed to secure it on contact with the final precision grip. A previous consensus was that the ttPG and the PGA itself, formed when trying to match the initial grasp to these object properties, are largely or exclusively products of feedforward planning, with the PGA consistently showing binocular advantages over monocular FV in neurotypical adults (Fig. 5A). However, alternative evidence has shown that visual feedback obtained during the 400 to 500 ms typically leading up to the peak grip strongly influences its size.[56,62,63] This revised interpretation is more consistent with another long-standing conclusion that the key dividend associated with normal binocular vision is in improving aspects of online grasp control,[34,53–55] and derives from retinal disparity processing in grasp-related areas of the lateral division of the dorsal/action stream of extrastriate cortex,[15,43] one of which, the anterior intraparietal sulcus (aIPS) area, is also particularly implicated in 3D object shape and size processing.[14,44]

The amblyopia group significantly increased their ttPG regardless of view or feedback, with the peak grip (Fig. 5) and grip size at initial object contact also increased in the subgroup whose stereoacuity was unmeasurable using standard clinical tests. Given these dissociations, it could be that the slower times to initial grip formation resulted from an overall slowing of the movements made by the amblyopia group, especially as this period substantially overlaps the acceleration phase of the reach (i.e., ttPV) and was found post hoc to be correlated with it under all view and feedback conditions ($r \geq 0.6$, $P \leq 0.001$). The wider, less accurate grip sizes at peak and at object contact produced by those with the poorest stereovision, however, more likely resulted from a combination of deficits in feedforward (with VPO) and feedback (with FV) control, due to their severely reduced access to disparity information, a situation that can also compromise 3D shape/size perception when only monocular cues are available,[64] perhaps involving defective processing in the laterodorsal aIPS area.

Finally, the amblyopic group showed increased grip application times and mis-grasping errors with the affected eye in both feedback conditions and in the binocular full vision condition compared to equivalent control performances (Fig. 4). Post hoc correlation analysis showed positive associations between the increases in these two parameters for each of the three conditions (all $r \geq 0.58$, $P < 0.01$), suggesting that they occurred for similar reasons. Mis-grasps, by definition, involved reapplications or reorientations of the grip immediately following contact with the goal object (e.g., Figs. 1B, 1D), suggesting that visual information normally used for guiding initial digit placements on the target was inadequate for a stable grasp, with haptic feedback from them indicating a need for adjustment. We have previously argued that amblyopic subjects prolong their GAT as an acquired, adaptive strategy that increases the availability of such non-visual feedback to compensate for uncertainties in their initial thumb/finger placements before attempting the object manipulation (e.g., lift) phase of the grasp.[34–36] The relatively more common requirement to alter the initial grip is consistent with these inadequacies and, in the comparative binocular FV conditions, is further consistent with suggestions that feedback derived from normal on-line stereovision is necessary to optimize grip application at object contact.[34] Neuroimaging studies further suggest that important nodes, such as the superior parieto-occipital cortex area, on the medial division of the dorsal/action stream, have special involvement in processing hand orientation and object contact points for endpoint grip application,[43,44] implying separate deficits in this other cortical circuit in amblyopia.

We have previously investigated prehension skills in neurotypical and amblyopic children under standard (full vision) conditions and shown that there is a developmental change in the way that both subject groups approach the task.[35,36] Specifically, younger children (5–6 years old) adopt a predominantly feedforward mode of control, with those 7 to 11 years old taking a progressively more integrated approach in which visual feedback is incorporated to guide their reach and grasp. We found that the performance of the 5- to 6-year-old children with amblyopia was particularly poor, much slower, and more error prone under all viewing conditions than at all later ages, including adulthood, but especially when using their affected eye, a situation resembling that of our current amblyopia group in the VPO condition. Taken together, these findings suggest that the prehension abilities of young amblyopic children might be relatively unaffected by the absence of feedback (i.e., with VPO), but would gradually worsen with age as the use of feedback becomes more significant, possibilities that would be interesting to examine in future work.

Our study had limitations, including relatively low subject numbers not atypical of this kind of work, with a heterogeneity of visual impairment among the amblyopia group, but which was needed to examine potential factors associated with their prehension deficits. We only assessed visual acuities at distance, not near, as in our test of stereoacuity, which was within the range of the prehension tasks and found to be related to some aspects of amblyopic adult performance. However, because previous studies[65] have reported no systematic differences between average distance and near acuities in amblyopic eyes, with any individual increases or decreases between the two measures typically < 1 line/0.1 logMAR, undetected associations with near acuity are unlikely. More importantly, we found that amblyopic subjects are capable of using visual feedback to improve their planning performance to an extent that was sometimes quite similar to that of the normal adults—for example, in reducing their binocular and Dom eye movement durations and low-velocity reach phases. But, we cannot identify the nature of the on-line feedback utilized for these purposes. Did it derive simply from a continuous view of the goal object with full vision or from information about the changing spatial relationship between the moving hand and digits as they approached the target? Inferences from previous work have favored the former possibility, as proficient use of the latter in control subjects (at least with binocular FV) appears based on processing of changing hand–target disparities,[34,53–55] to which amblyopic adults with reduced stereovision have limited access. Future studies comparing the performance of these subjects with different sources of feedback available will be required to answer this question.

The data obtained from the amblyopic adults were complex, reflecting the complexity of the causes of their impaired eye–hand coordination skills, with suggestions that they may not construct internal models for anticipatory control with their affected eye, and they have generalized reach planning deficits and difficulty using on-line visual feedback for enhancing grasp proficiency, possibly resulting from separate problems in different dorsal stream cortical subcircuits. Given these considerations, it seems unlikely that any generic or even individually tailored instructional training regime would lead to substantial improvements in their overall prehension skills, as such regimes typically target specific deficiencies in off-line control. Instead, we suggest that the most viable approaches to pursue in the future are those specifically designed to rehabilitate binocular functions in amblyopic subjects,[26–28,66] some of which have already shown promise for improving multiple components of fine visuomotor performance.[67–69]

Acknowledgments

Disclosure: **S. Grant**, None; **M.L. Conway**, None

References

1. Hashemi H, Pakzad R, Yekta A, Bostamzad P, Aghamirsalim M, Sardari S. Global and regional estimates of prevalence of amblyopia: a systematic review and meta-analysis. *Strabismus*. 2018;26:168–183.
2. Holmes JM, Clarke MP. Amblyopia. *Lancet*. 2006;367:1343–1351.
3. Barnes G, Hess RF, Dumoulin SO, Achtman RL, Pike GB. The cortical deficit in humans with strabismic amblyopia. *J Physiol*. 2001;533:281–297.
4. Muckli L, Kieβ S, Tonhausen N, Singer W, Goebel R, Sieteanu R. Cerebral correlates of impaired grating perception in individual, psychophysically assessed human amblyopes. *Vision Res*. 2006;46:506–526.
5. Lerner Y, Hendler T, Malach R, et al. Selective fovea-related deprived activation in retinotopic and higher-order visual cortex of human amblyopes. *NeuroImage*. 2006;33:169–179.
6. Li X, Mullen KT, Thompson B, Hess RF. Effective connectivity anomalies in human amblyopia. *NeuroImage*. 2011;54:505–516.
7. Sengpiel F, Blakemore C. The neural basis of suppression and amblyopia in strabismus. *Eye (Lond)*. 1996;10:250–258.
8. Conner IP, Odom JV, Schwartz TL, Mendola JD. Retinotopic maps and foveal suppression in the visual cortex of amblyopic adults. *J Physiol*. 2007;583:159–173.
9. Li J, Thompson B, Lam CSY, et al. The role of suppression in amblyopia. *Invest Ophthalmol Vis Sci*. 2011;52:4169–4176.
10. Clavagnier S, Dumoulin SO, Hess RF. Is the cortical deficit in amblyopia due to reduced cortical magnification, loss of neural resolution, or neural disorganization? *J Neurosci*. 2015;35:14740–14755.
11. Farivar R, Zhou J, Huang Y, Feng L, Zhou Y, Hess RF. Two cortical deficits underlie amblyopia: a multifocal fMRI analysis. *NeuroImage*. 2019;190:232–241.
12. McKee S, Levi D, Movshon A. The pattern of visual deficits in amblyopia. *J Vis*. 2003;3:380–405.
13. Quinlan DJ, Culham JC. fMRI reveals a preference for near viewing in the human parieto-occipital cortex. *NeuroImage*. 2007:36;167–187.
14. Georgieva A, Peeters R, Kolster H, Todd JT, Orban GA. The processing of three-dimensional shape from disparity in the human brain. *J Neurosci*. 2009:29;727–742.
15. Kiorpes L, Daw N. Cortical correlates of amblyopia. *Vis Neurosci*. 2018:35;E016.
16. Ho CS, Giaschi DE. Stereopsis-dependent deficits in maximum motion displacement in strabismic and anisometropic amblyopia. *Vision Res*. 2007;47:2778–2785.
17. Gao Y, Reynaud A, Tang Y, Feng L, Zhou Y, Hess RF. The amblyopic deficit for 2nd order processing: generality and laterality. *Vision Res*. 2014;114:111–121.
18. Levi DM, Klein SA. Spatial localization in normal and amblyopic vision. *Vision Res*. 1983;23:1005–1017.
19. Hess RF, Holliday IE. The spatial localization deficit in amblyopia. *Vision Res*. 1992;32:1319–1339.
20. Piano MEF, Bex PJ, Simmers AJ. Perceptual visual distortions in adult amblyopia and their relationship to clinical features. *Invest Ophthalmol Vis Sci*. 2015;55:5533–5542.
21. Sharma V, Levi DM, Klein SA. Undercounting features and missing features: evidence for a high-level deficit in strabismic amblyopia. *Nat Neurosci*. 2000;3:496–501.
22. Ho CS, Paul PS, Asirvatham A, Cavanagh P, Cline R, Giaschi DE. Abnormal spatial selection and tracking in children with amblyopia. *Vision Res*. 2006;46:3274–3283.
23. Farzin F, Norcia AM. Impaired visual decision-making in individuals with amblyopia. *J Vis*. 2011;11:1–10.
24. Hou C, Kim Y-L, Lai XJ, Verghese P. Degraded attentional modulation of cortical neural populations in strabismic amblyopia. *J Vis*. 2016;16(3):1–16.
25. Grant S, Moseley MJ. Amblyopia and real-world tasks. *Strabismus*. 2011;19:119–128.
26. Birch EE. Amblyopia and binocular vision. *Prog Ret Eye Res*. 2013;33:67–84.
27. Levi DM, Knill DC, Bavalier D. Stereopsis and amblyopia: a mini-review. *Vision Res*. 2015;114:17–30.
28. Niechwiej-Szwedo E, Colpa L, Wong AMF. Visuomotor behaviour in amblyopia: deficits and compensatory adaptations. *Neural Plast*. 2019;2019:6817839.
29. Hrisos S, Clarke MP, Kelly T, Henderson J, Wright CM. Unilateral visual impairment and neurodevelopmental performance in preschool children. *Br J Ophthalmol*. 2006;90:836–838.
30. Schiller PH, Kendall GL, Kwak MC, Slocum WM. Depth perception, binocular integration and hand-eye coordination in intact and stereo impaired human subjects. *Clin Exp Ophthalmol*. 2012;3(2):1–12.
31. O'Connor AR, Birch EE, Anderson S, Draper H, FSOS Research Group. The functional significance of stereopsis. *Invest Ophthalmol Vis Sci*. 2010;51:2019–2023.
32. Piano MEF, O'Connor AR. The effect of degrading binocular single vision on fine visuomotor skill task performance. *Invest Ophthalmol Vis Sci*. 2013;54;8204–8213.
33. Grant S, Melmoth DR, Morgan MJ, Finlay AL. Prehension deficits in amblyopia. *Invest Ophthalmol Vis Sci*. 2007:48;1139–1148.
34. Melmoth DR, Finlay AL, Morgan MJ, Grant S. Grasping deficits and adaptations in adults with stereo vision losses. *Invest Ophthalmol Vis Sci*. 2009:50;3711–3720.

35. Suttle CM, Melmoth DR, Finlay AL, Sloper JJ, Grant S. Eye–hand coordination skills in children with and without amblyopia. *Invest Ophthalmol Vis Sci* 2011;52:1851–1864.
36. Grant S, Melmoth DR, Conway ML, Sloper JJ. Age- and stereovision-dependent eye-hand coordination deficits in children with amblyopia and abnormal binocularity. *Invest Ophthalmol Vis Sci*. 2014;55:5687–5715.
37. Grant S, Conway ML. Reach-to-grasp deficits in amblyopia: effects of object contrast and low visibility. *Vision Res*. 2015;114:100–110.
38. Desmurget M, Grafton S. Forward modelling allows feedback control for fast reaching movements. *Trends Cogn Sci*. 2000;4:423–431.
39. Elliot D, Helsen WF, Chua R. A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychol Bull*. 2010;127:342–357.
40. Zhao H, Warren WH. On-line and model-based approaches to the visual control of action. *Vision Res*. 2015;110:190–202.
41. Monaco S, Cavina-Patesi C, Sedda A, Fattori P, Galletti C, Culham JC. Functional magnetic resonance adaptation reveals the involvement of the dorsomedial stream in hand orientation for grasping. *J Neurophysiol*. 2011;106:2248–2263.
42. Glover S, Wall MB, Smith AT. Distinct cortical networks support the planning and online control of reaching-to-grasp in humans. *Eur J Neurosci*. 2012;35:909–915.
43. Begliomini C, De Sanctis T, Marangon M, et al. An investigation of the neural circuits underlying reaching and reach-to-grasp movements: from planning to execution. *Front Hum Neurosci*. 2014;8:876.
44. Monaco S, Sedda A, Cavina-Pratesi C, Culham JC. Neural correlates of object size and object location during grasping actions. *Eur J Neurosci*. 2015;41:454–465.
45. Budisavljevic S, Dell'Acqua F, Castiello U. Cross-talk connections underlying dorsal and ventral stream integration during hand actions. *Cortex*. 2018;103:224–239.
46. Mon-Williams M, Dijkerman HC. The use of vergence information in the programming of prehension. *Exp Brain Res*. 1999;128:578–582.
47. Greenwald HS, Knill DC, Saunders JA. Integrating visual cues for motor control: a matter of time. *Vision Res*. 2005:45;1975–1989.
48. Melmoth DR, Storoni M, Todd G, Finlay AL, Grant S. Dissociation between vergence and binocular disparity cues in the control of prehension. *Exp Brain Res*. 2007;183:283–298.
49. Niechwiej-Szwedo E, Goltz H, Chandrakumar M, Hirji ZA, Wong AMF. Effects of anisometropic amblyopia on visuomotor behaviour: III. Temporal eye-hand coordination during reaching. *Invest Ophthalmol Vis Sci*. 2011;52:795–803.
50. Niechwiej-Szwedo E, Goltz HC, Chandrakumar M, Wong AM. The effect of sensory uncertainty due to amblyopia (lazy eye) on the planning and execution of visually-guided 3D reaching movements. *PLoS One*. 2012;7(2):e31075.
51. Niechwiej-Szwedo E, Goltz H, Colpa L, Chandrakumar M, Wong AM. Effects of reduced acuity and stereoacuity on saccades and reaching movements in adults with amblyopia and strabismus. *Invest Ophthalmol Vis Sci*. 2017;58:914–921.
52. Buckley JG, Pacey IE, Panesar GK, Scally A, Barrett BT. Prehension of a flanked target in individuals with amblyopia. *Invest Ophthalmol Vis Sci*. 2015;56:7568–7580.
53. Watt SJ, Bradshaw MF. Binocular cues are important in controlling the grasp but not the reach in natural prehension movements. *Neuropsychologica*. 2000;38:1473–1481.
54. Loftus A, Servos P, Goodale MA, Mendarozqueta N, Mon-Williams M. When two eyes are better than one in prehension: monocular viewing and end-point variance. *Exp Brain Res*. 2004;158:317–327.
55. Melmoth DR, Grant S. Advantages of binocular vision for the control of reaching and grasping. *Exp Brain Res*. 2006;171:371–388.
56. Grant S, Conway ML. Some binocular advantages for planning reach, but not grasp, components of prehension. *Exp Brain Res*. 2019;237:1239–1255.
57. Kumaran SE, Khadka J, Baker R, Pesudovs K. Functional limitations recognized by adults with amblyopia and strabismus in daily life: a qualitative exploration. *Ophthalmic Physiol Opt*. 2019;39:131–140.
58. Wolpert DM, Diedrichsen J, Flanagan JR. Principles of sensorimotor learning. *Nat Rev Neurosci*. 2011;12:739–751.
59. Miles CAL, Wood G, Vine SJ, Vickers JN, Wilson MR. Quiet eye facilitates visuomotor coordination in children with developmental coordination disorder. *Res Dev Disabilities*. 2015;40:31–41.
60. Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologica*. 1971:9;97–112.
61. Jakobson LS, Goodale MA. Factors affecting higher-order movement planning: a kinematic analysis of human prehension. *Exp Brain Res*. 1991:86;199–208.
62. Paulignan Y, Frak VG, Toni I, Jeannerod M. Influence of object position and size on human prehension movements. *Exp Brain Res*. 1997;114:226–234.
63. Fukui T, Inui T. The effect of viewing the moving limb and target object during the early phase of movement on the online control of grasping. *Hum Mov Sci*. 2006;25:349–371.
64. Sawamura H, Gillebert CR, Todd JT, Orban GA, Binocular stereo acuity affects monocular three-dimensional shape perception in patients with strabismus. *Br J Ophthalmol*. 2018;102:1413–1418.
65. Christoff A, Repka MX, Kaminski BM, Holmes JM, Pediatric Eye Disease Investigator Group. Distance versus near visual acuity in amblyopia. *J AAPOS*. 2011;15:342–344.
66. Mansouri B, Thompson B. A binocular approach to treating amblyopia: antisuppression therapy. *Optom Vis Sci*. 2010:87;697–704.
67. Vedamurthy I, Nahum M, Huang SJ, et al. A dichoptic custom-made action video game as a treatment for adult amblyopia. *Vision Res*. 2015;114:173–187.
68. Vedamurthy I, Knill DC, Huang SJ, et al. Recovering stereo vision by squashing virtual bug in a virtual reality game. *Philos Trans R Soc B Biol Sci*. 2016;371:20150264.
69. Webber AL, Wood JM, Thompson B. Fine motor skills of children with amblyopia improve following binocular treatment. *Invest Ophthalmol Vis Sci*. 2016;57:4713–4720.