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Eye-Hand Coordination Skills in Children with and without Amblyopia

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Summary

Purpose: To investigate whether binocular information provides benefits for programming and guidance of reach-to-grasp movements in normal children and whether these eye-hand coordination skills are impaired in children with amblyopia and abnormal binocularity.

Methods: Reach-to-grasp performance of the preferred hand under binocular versus monocular (dominant or non-dominant eye occluded) conditions to different objects (2 sizes, 3 locations, 2-3 repetitions) was quantified using a 3D motion-capture system. Participants were 36 normally-sighted children (aged 5-11) and 11 adults, and 21 children (aged 4-8) with strabismus and/or anisometropia. Movement kinematics and error rates were compared for each viewing condition within- and between-subject groups.

Results: The youngest control subjects employed a mainly programmed (ballistic) strategy and collided with the objects more often when viewing with only one eye, while older children progressively incorporated visual feedback to guide their reach and, eventually, their grasp, resulting in binocular advantages for both movement components resembling those of adult performance. Amblyopic children were the worst performers under all viewing conditions, even for the dominant eye. They spent almost twice as long in the final approach to the objects and made many (1.5-3 times) more errors in reach direction and grip positioning as their normal counterparts, these impairments being most marked in those with the poorest binocularity, regardless of the severity or cause of their amblyopia.

Conclusions: The importance of binocular vision for eye-hand coordination normally increases with age and use of ‘on-line’ movement guidance. Restoring binocularity in children with amblyopia may improve their poor hand action control.

Paper Description: Abnormal binocularity in association with poor spatial vision in one eye (amblyopia) is common in childhood. We report that reaching and grasping is impaired in children with these conditions, not only when viewing binocularly or with their amblyopic eye, but with their dominant eye too.

The acquisition of precise eye-hand coordination for reaching, grasping and manipulating objects was a major step in human evolution and is essential to many of our everyday activities. Quantitative evidence shows that normal adults perform these hand actions with much higher speed, accuracy and success in task completion when using binocular vision compared to conditions in which their functional stereovision is reduced by monocular occlusion[1-6] or image blur[7]. Natural developmental reductions in functional binocularity occur in a variety of disorders, some of which are associated with unilateral amblyopia, characterized by visuospatial deficits in resolution, contrast and positional acuity in one eye[8,9]. Common causes are strabismus (eye misalignment) and anisometropia (refractive imbalance) during the susceptible period (up to age 7-8 years)[10,11] each of which can result in different relative losses in visual acuity versus binocular stereo vision[9].

From the viewpoint of clinical significance and management, there is growing interest in whether these disorders adversely affect the patient's ability to perform everyday tasks including those that require skilled eye-hand coordination and, if so, whether the impairments result from abnormal development of binocular or monocular spatial vision. We recently examined these issues by comparing the reach-to-grasp performance of normal adults with that of strabismic and/or anisometropic adults who had persistent amblyopia[12] or selectively reduced stereovision[13]. The key findings were that performance of patients with the worst (clinically undetectable) stereo acuity – regardless of any accompanying amblyopia – with both eyes open was generally poorer than those with residual ('coarse') stereopsis, and very similar to their own performance and to that of normal adults using just the dominant eye. This evidence suggests that high-grade binocular stereovision is necessary for skilled eye-hand coordination and that the presence of adequate visual acuity in each of the two eyes cannot compensate for its loss, even over the longer-term

Here we extend this work to 4-8 year-old children with different stereo vision losses due to strabismic and/or anisometropic amblyopia, with the aim of determining whether they, too, show binocular reach-to-grasp impairments compared to developmentally-normal peers, in association with their reduced binocularity. Several considerations indicate that they should. Marked improvements in the primitive 'pre-reaching' of early infancy correlate with the rapid appearance of disparity sensitivity at around 4-6 months of age[14,15], with binocular vision already showing some benefits over a monocular view for purposeful reaching behavior[16]. Moreover, while the maturation of stereo acuity typically appears complete by 5 years of age[17,18], eye-hand coordination skills continue to develop further, probably into the second decade of life[19-22]. It is also known that the spatial and binocular deficits in strabismic and anisometropic amblyopia are associated with abnormal development of the primary visual (V1) cortex and of higher level cortical areas[23,24], perhaps because they inherit processing abnormalities from V1 or arise there independently. These higher areas include ventral regions of occipito-temporal cortex concerned with perceptual encoding of object properties that might be useful for action planning, and dorsal regions of occipito-parietal cortex concerned with spatial vision and more directly involved in hand movement programming and visual guidance[25-27]. Indeed, anatomical abnormalities (reduced grey matter thickness) have been shown to be more pronounced in these higher areas in children with both types of amblyopia than in adults with these disorders[28], implying that their eye-hand coordination may be more seriously impaired than in these older subjects.

Other evidence, however, casts doubt on this assumption. The normal acquisition of mature reaching and grasping skills appears to evolve non-uniformly[19-22], rather than gradually, during childhood, with vision used in different ways to control these movements at different ages. For example, children aged 5-6 years seem to use a ‘feedforward’ approach, in which their reach-to-grasp actions are mainly determined by motor programming based on visual information about the goal object (e.g., its distance, size and shape) obtained prior to movement onset, while 7-8 year olds switch to using ‘on-line’ visual feedback to guide their hand towards the target, with more adult-like integration of both control strategies acquired only at 9-11 years of age. Adult studies suggest that while binocular vision normally provides some benefits for movement programming, its advantages are most evident during the guidance phase, when the moving hand generates disparity changes as it finally approaches and grasps the object. Consistent with this, Watt et al. (2003)[29] found few major differences in binocular versus monocular reach-to-grasp movements among normal 5-6 year old children, whereas 10-11 year olds showed significantly faster final approach times when using both eyes, as do normal adults. The absence of a clear binocular advantage in the younger age-group may thus imply that reduced binocularity in amblyopic children of equivalent age will have little or no adverse effect on their eye-hand coordination abilities.

MATERIALS AND METHODS

This study was approved by the human research ethical committees of City University London and Moorfields Eye Hospital. Prior to recruitment, methods were explained to the prospective subject and parent (in the case of children), who gave assent or consent for participation. Its conduct adhered to the tenets of the Declaration of Helsinki.

Part 1: Normal Development

Thirty-six children (aged 5-11 years) and 11 adults (aged 20-42 years) who met our inclusion criteria were recruited, following pre-screening of almost 100 potential participants. Exclusion criteria were: (1) a history of neurological disorder or ocular anomaly that might be a risk factor for amblyopia; (2) spectacle wear; (3) uncorrected (logMAR) visual acuity (VA) of $\geq$0.2 in either eye; (4) interocular acuity difference (IOD) >0.1; (5) stereo acuity (SA) >100 arc secs (Wirt-Titmus test, Stereo Optical Co. Inc); and (6) no strong hand preference ($\leq$ ±67, abbreviated Edinburgh Handedness Inventory[30]). The children were divided into three age groups, defined as early (5-6 years), middle (7-8 years) and late (9-11 years) childhood (see Table 1 for summary). These age ranges were selected based on evidence that developmental changes in visuomotor control normally occur between them[19-22] and because they correspond to ages within a period of visual plasticity during which amblyopia may develop and is most amenable to treatment[8-11]. Sighting eye tests were administered to establish the participant's ocular dominance and their arm lengths (from acromion to wrist) were measured to determine their maximal comfortable reaching distance.

[Table 1, near here]

Part 2: Normal versus Amblyopic children

Twenty-one children, aged 4 to 8 years, with unilateral amblyopia were recruited from the patient populations of Moorfields Eye Hospital or the Optometry clinic at City University London. These children had a history of strabismus and/or anisometropia, but no systemic or ocular pathology. Data on their current logMAR visual acuities, refractive status, and stereo acuity (Wirt-Titmus and/or Frisby tests) were collected from records of orthoptic assessments made on the day of recruitment and testing (see Table 2 for details). All were undergoing amblyopia management, although only 12 had successfully completed the treatment regime involving refractive correction and part-time occlusion of the better (dominant) eye: the others had yet to begin patching or had not been entirely compliant with it. Data on hand preference[30] and arm length were collected just prior to testing. The patients were sub-divided in subsequent analyses on the basis of their IOD as having mild (IOD 0.11-0.3; n=10) or moderate-to-severe (IOD $\geq$ 0.31; n=11) amblyopia, and from their SA threshold into different sub-groups having 'coarse' (55-3000 arc secs; n=10) or 'negative' (unmeasurable; n=11) sensitivities to binocular disparity (see Table 2 for details). Note that the stereo acuities of 3 subjects defined as having 'coarse' stereopsis were within the normal range (55-85"), a point considered further in Results.

[Table 2 & Figure 1, near here]

Hand movement recordings

Subjects sat on an adjustable chair at a table with a matt black surface gripping (between the thumb and index finger of their preferred hand) a 30 mm diameter 'start button' positioned along their midline at a distance of 12 cm. Lightweight infra-red (IR) reflective markers were placed using Blu-tack on the thumb and index finger nails of their preferred hand and on the wrist using a Velcro strap. A reflective marker was also placed on top of each of the two cylindrical household objects which were the targets in the testing procedures. The 3D spatial coordinates of these markers were tracked by three wall-mounted IR emitting and detecting cameras (Proflex; Qualisys AB, Gothenburg, Sweden) at a sampling rate of 60Hz for a period of three seconds, with a spatial resolution of <0.5mm.

Throughout the testing, control subjects wore liquid crystal (PLATO) spectacles (Translucent Technologies, Canada), the lenses of which were occluded between trials, but opened suddenly to signal that the next movement should begin. Three viewing conditions were used – binocular; monocular dominant (DOM) sighting eye; monocular non-dominant (ND) eye. In monocular conditions, the PLATO lens over the non-tested eye remained occluded. Recording onset was triggered manually (by computer key press) which simultaneously opened one or both spectacle lenses. The amblyopic subjects, however, were tested while wearing their prescribed spectacle correction which did not fit comfortably behind the PLATO glasses. So, instead, they sat with their eyes closed between trials, and started their movement on a verbal 'go' command, with the non-tested eye occluded by a black 'pirate' patch under their spectacles on monocular trials. For these reasons, their reaction times (see below) could not be accurately recorded.

The subject's task was to reach for, precision grasp (between thumb and index finger) the object (at about half its height), and move it to another location on the table, before returning their hand to the start position. The task was explained to the subject while seated at the table, along with instructions to move as naturally and accurately as possible, such as 'like you would do at home' and 'it's not a race'. Practice trials were given before the experiment began, to ensure that the instructions were understood. The two objects were a glue stick and a pill bottle of equal (100 mm) height, but of 'small' (24 mm) and 'large' (48 mm) diameter, respectively. They were placed at 3 different positions (see Fig.1): one at a near location along the subject's midline, and two further away and 10^{o} off-midline, either on the same side as the subject's preferred hand or on the opposite side. Reaching distances were scaled to arm length. Specifically, midline and far distances of 12 and 20 cm, 18 and 30 cm and 25 and 40 cm were marked on the table surface by 3 sets of colored stickers and used for arm lengths of 25-34 cm, 35-44 cm and $\geq$45 cm, respectively, which generally applied to the early, middle and older (plus adult) age-groups. Object dimensions were not similarly scaled for hand size, because this would not accord with the subject's real-world experience. Participants completed 12 or 18 trials under each viewing condition (2 sizes x 3 positions x 2 or 3 repeats), depending on their age and level of cooperation, in a blocked design, counter-balanced between subjects in each age-group. Within each viewing condition, the trial order was in the same pseudo-randomized sequence, with counter-balancing for object size and position. The sequences differed, however, between conditions, and so were unpredictable (see Supplementary Table S1 for details). Any trials in which the subject failed to move or to lift the object as instructed were repeated at the end of the block. Testing typically took ~30 minutes.

Data analysis

Marker tracking data were collected using Qualisys Track Manager and examined off-line using customized programs in Matlab software (The Mathworks, Natick, USA). Key kinematic parameters of the movement were determined for each trial, with profiles of the wrist velocity and spatial path, and of the aperture between thumb and index finger representing the grip examined for on-line corrections or errors (see Results, Figs. 8 & 9). As in our previous work[6,7,12,13] the moment of movement onset (MO) was defined as the first recording frame in which the velocity of the marker on the wrist first exceeded 50mm/s, with the moments of initial object contact and the movement end-point defined as frames in which the object marker was first moved in 3D space by $\geq$1mm and $\geq$10 mm, respectively. Two general parameters were derived from the wrist marker. These were: (1) the **reaction time** (RT) – from initial lens opening to MO – which is a product of movement planning and programming; and (2) the **movement time**

(MT), representing the total execution phase, from movement start to finish. Note: reaction time measures were only obtained in control subjects in whom recordings were synchronized with lens opening.

Dependent measures obtained from the wrist marker were also used to examine reaching performance (see Fig.2A). These included: (3) the overall **reach duration,** from MO to initial object contact; along with two parameters of reach programming – (4) its **peak velocity** and (5) the **time to peak deceleration** (PD) – known to scale with assessments of absolute target distance made prior to MO[1-3,5-7] and (6) the final **low velocity phase** (LVP) of the reach (from PD to object contact). This last guidance phase generally scales with absolute target distance too, but – in addition – is believed to be strongly influenced by visual feedback concerning the on-going reduction in relative distance (i.e., depth) between the moving hand and the target[1-3,5-7]. Uncertainty about this changing depth relationship may result in 'on-line' corrections or 'errors' occurring in the given movement profile. Three types of error were identified at this reaching end-stage: (7) **pre-contact velocity corrections** – additional 'peaks' or flat 'plateaus' (lasting >50 ms) in the wrist velocity profile (see Fig.8B); (8) **pre-contact spatial path adjustments** representing changes in direction in the wrist trajectory profile; and (9) **collisions**, involving abrupt termination of the velocity profile with no obvious 'braking' (i.e., LVP) accompanied by a wide grasp at object contact (in the grip aperture profile). Errors (7) and (8) may be interpreted as under-reaching actions, and error (9) as over-reaching the target with failure to adequately close the grip[6,7].

Dependent measures of grasping performance were mainly assessed from the markers on the thumb and index finger (see Fig.2B). These included two parameters of grip programming known to scale with assessments of the object size-distance relations[1-3,5-7] – (10) the width of the **peak grip** (PG) at hand 'pre-shaping' and (11) the **time to peak grip** after MO – along with the next three sub-actions of the grasping sequence, (12) the **grip closure time** (from PG to initial object contact), (13) the **grip size at contact**, and (14) the **grip application time** (from contact to the movement end-point when the object was usually being lifted).

The period after PG also represents distinct guidance phases of the grasp, in which different corrections or errors may be apparent. These were: (15) **pre-contact grip adjustments** – extra opening/closures or flat plateaus (lasting >50 ms) in the aperture profile between thumb and finger just before the object was contacted (see Fig.9B); (16) **wide initial contacts** defined, empirically, by an aperture >1.5 times the large object's diameter or >2 times the small object's diameter, but with no evidence of a collision in the velocity profile of the same trial[6,7,12,13]; (17) **post-contact hand corrections** – additional peaks or plateaus in the velocity (see Fig.8B) or spatial path profiles after object contact; (18) **post-contact grip adjustments** – extra opening/closures in the aperture profile after object contact (see Fig.9B) and (19) **prolonged contacts** – flat plateaus or 'tails' (lasting >150 ms) in the post-contact phase of the grip profile. Errors (15) and (16) are indicative, respectively, of a need to correct the digit positions while they were still 'in flight' and of inaccurate scaling of the initial grip to the object's true size. Corrections (17) and (18) suggest a need to modify the hand and/or grip positions because of errors in the original digit placement(s), with prolonged contacts (19) suggesting a delay in lifting the object while non-visual (e.g., tactile, kinesthetic) feedback was used to confirm that the grip was secure[6,7,12,13].

Finally, we assessed two aspects of temporal coordination between the reach and grasp which occur near-simultaneously in normal adults under natural viewing conditions, but tend to de-couple when binocular vision is unavailable[6]. These were: (20) the **peak deceleration-to-peak grip** – the difference in timing between the occurrence of these programmed components of the two movements; and (21) the difference **at object contact** between the moment that the hand first touched the target and the minimum wrist velocity at reach termination. Note: large positive values of these parameters signify loss of coordination, with the PD occurring much earlier than the peak grip or with object contact substantially preceding the end of the reach.

Median values obtained for all trials under each of the three viewing conditions were calculated separately for each kinematic parameter (i.e., measures 1-6, 10-14 and 20-21, above). Since the trial number varied (from 12 to18) between participants, the rate of occurrence of each error type (i.e., measures 7-9 and 15-19, above) was determined from their absolute numbers as a proportion of the total number of trials completed. Main effects of view within each normal age-group were explored using repeated-measures ANOVA (SPSS UK Ltd., Woking, UK). Because subjects at two younger ages reached to shorter distances (in accordance with their arm lengths) and distance has a very strong effect on most kinematic measures – except for reaction times and the grip size at object contact – some landmarks of the movement dynamics (e.g., time in the LVP) were also calculated as a percentage of the total movement time on each trial. These measures and error-rates were further compared in the ANOVA, with age as a between-subjects factor. We also made between-group comparisons of all these performance measures in visually normal versus amblyopic children. For this purpose, the patients were matched to appropriate normal subjects, identified by similarities in age, gender and handedness (unpaired t-tests, $p>0.05$), resulting in a new control group (n=15) comprising of the 11 early and 4 intermediate aged-children from the first experiment. Between-group factors employed in these analyses were subject type (controls, amblyopes), degree of amblyopia (none, mild, moderate-to-severe) and stereo acuity (high-grade, coarse, negative). Planned pair-wise comparisons undertaken post hoc employed the Bonferroni test. Significance levels were set at $p<0.05$.

Results

Part 1: Normal developmental changes in reach-to-grasp performance

In this section we examine age-related changes in the visuomotor control strategies adopted and in the benefits afforded by binocular vision on our reach-to-grasp paradigm. For ease of presentation, data related to the latter issue are given only by comparison with use of the sighting (DOM) eye, as monocular performance was similar when using the ND eye. Details of the median kinematic measures and mean error-rates obtained for subjects in each age-group as a function of binocular versus DOM eye viewing are given, respectively, in Supplementary Tables S2 & S3.

[Figures 2 & 3, near here]

Age-related changes in visuomotor control

There were several main effects of age on kinematic performance which did not interact with viewing condition. The overall reaction times when using binocular or DOM eye vision (Supplementary Table S2) of children in the early (909 msecs) and middle (838 msecs) age-groups were ~1.5-1.8 times greater than those of the oldest children and adults ($p<0.01$ for all comparisons), suggesting that they spent much longer extracting visual information about the goal object when planning and programming their movements. The 5-6 year old children then spent a greater percentage of their subsequent movement execution in the programmed phases of the reach and grasp (i.e., up to PD and PG, respectively) and significantly less proportional time visually guiding the LVP of the reach and closure of their grip (Fig.3) compared to the adult participants ($p<0.02$ for all comparisons). The middle children aged 7-8 years, however, showed a more adult-like division of time between the programmed and guidance phases of the reach, but retained an immature distribution of time in controlling their grasp, while the behavior of the oldest children did not differ significantly from adult performance (Fig.3). These findings suggest that the youngest children adopted a mainly programmed (feedforward) approach to the task, with children at intermediate ages beginning to incorporate visual feedback to guide their reach, before emergence in the 9-11 year olds of more balanced (mature) feedforward-feedback control of both movement components.

The developmental increase in guidance time was accompanied by an overall reduction in reaching and grasping error-rates late in the movements and an improvement in end-point accuracy (Supplementary Tables S2 & S3). For example, median grip sizes formed by the adult subjects at contact were significantly closer to the average physical diameter (36 mm) of the two objects and they produced fewer wide initial contacts (both $p<0.001$) compared to the children in each age-range ($p<0.01$, for all comparisons). Indeed, a reduction in errors and increase in grip accuracy at contact were the main changes – along with faster reach velocities to comparable target locations (see Figs. 4 & 6) – that occurred after 9-11 years of age.

[Figures 4-6, near here]

Age-related changes in the benefits of binocular vision

Virtually every aspect of the adult subjects' reach-to-grasp performance benefited significantly from the availability of binocular vision, in accord with previous findings[1-7], but the two groups of younger children exhibited few – and different – binocular advantages over viewing with one eye occluded (Supplementary Tables S2 & S3). At age 5-6 years these advantages were largely confined to aspects of movement programming, including faster reaction times, and better (more linear) scaling of their peak reach velocity to target position (Fig.4) and peak grip aperture to object size (Fig.5). This latter effect, in which they selectively widened their PG prior to grasping the smaller object when using one eye alone was present at all four ages examined (view x size interactions, all $p<0.015$), and is generally interpreted as adding a safety margin for error[1-3,5-7].

However, the monocular peak velocity scaling of the early children was unusual. Like the other subjects, when binocular vision was available to assess the object's spatial location, their reaching increased markedly in peak velocity for the midline-near to ipsi-far to contra-far positions (Fig.4). But unlike the other age-groups, who reduced their PV to all positions when viewing with the DOM eye, the 5-6 year old children actually moved faster to midline-near targets and with almost equal velocity as to the contra-far location (view x position interaction, p=0.047). This implies that they were more uncertain about (or took less account of) the object's position when programming their reach with monocular vision. In accord with these possibilities and their generally 'ballistic' approach, they contacted the objects with a wider grip (p=0.01) after making more (p=0.045) very late corrections to their reach velocity when using their DOM eye alone (Supplementary Tables S2 & S3). More particularly, unlike the other age-groups, they collided with (and knocked down) the object much more often than when viewing binocularly (p=0.02; Fig.6A), especially when it was the smaller (less stable) target at the midline-near location (size x position interaction, p=0.046).

The children of intermediate ages also showed binocular advantages for movement programming (e.g., Figs.4 & 5) but, in addition, their movement execution times were substantially reduced (by ~100 msecs) when viewing with both eyes ($p<0.001$), due to faster PV reaches, reach durations and grip application times (all $p<0.05$). With monocular viewing, these subjects also made significantly more hand and grip adjustments (both $p<0.02$) after object contact (Fig.6C), which we have previously associated with rectifying inaccuracies in initial digit placement[6,7,12,13]. Further benefits of binocular vision were present in the children aged 9-11 years. Crucially, these included selective reductions in time (of ~60-100 msec) spent visually guiding the LVP of the reach and their grip closure, along with improved reach-grasp coordination at initial contact compared to monocular viewing (all, $p<0.01$), these being hallmarks of the advantages of binocular vision in normal adults (Supplementary Table S2). The older children also showed a similar pattern of reductions in binocular versus DOM eye error-rates before and after object contact (Fig.6B,C) to those of our adult subjects (Supplementary Table S3).

In sum, we found that the importance of binocular information for efficient reach-to-grasp performance increased during normal childhood development, becoming more marked along with the use of vision to guide the two movement components. One might thus reasonably suppose that the abnormal binocularity of amblyopic children in the early-to-middle (5-8 year) age-range will have few adverse effects on their binocular reach-to-grasp abilities, although deficits might be expected when performing the task with just their affected eye when, as in adult amblyopes[12], its VA loss was moderate-to-severe.

[Tables 3 & 4, near here]

Part 2: Normal versus Amblyopic children

Benefits of Binocular Vision

The new, combined, control group of 5-8 year-olds showed binocular advantages for improving grip accuracy at contact (Table 3) and reducing late reach velocity corrections and collisions (Table 4) compared to viewing with either eye alone ($p<0.025$, for all comparisons), in line with the preponderance of these benefits in the early-age children from Part 1 of the study. Binocular vision also provided significant benefits over both the dominant and affected eye in the children with amblyopia, but only for reducing collisions and grip adjustments after contact (Table 4). This latter effect more resembled the binocular performance of normal 7-8 year olds. Indeed, the amblyopic children also showed similar view-dependent scaling of their PV to target location and PG to object size (data not shown) as the normal middle age-group. That is, their increased monocular collision-rate was not associated with defective peak reach velocity scaling, as in normal 5-6 year olds (Fig.4). Binocular viewing also appeared to provide an advantage for this reach parameter and to result in an earlier time to peak grip and improved grip accuracy at contact (Tables 3, 4), but these effects were solely due to poorer performance when using the amblyopic eye alone (all $p<0.05$). There were no significant differences between fellow and affected eye viewing in the children with amblyopia.

[Figures 7-9, near here]

Effects of viewing condition

More strikingly, direct comparisons between subject-types (Tables 3 & 4, column 8) demonstrated that the reach-to-grasp behavior of the amblyopic children was quite different from their normally-sighted peers. Of the 20 movement parameters examined, 13 showed significant between-group effects, all but one being directly indicative of poorer performance by the amblyopic children. These effects appeared to occur across binocular, affected/non-dominant eye, and even fellow/dominant eye viewing conditions, because there were no significant interactions between view and subject-type. The major differences, in comparison to the control group, were ~25-75% increases in overall movement durations and in time spent in the LVP of the reach, in grip closure and application (Fig.7), along with 20-220% increases in most error-rates during these guidance phases (Figs.8 & 9). These latter included more spatial adjustments in reach direction ($p=0.009$) and grip position ($p=0.006$) just prior to contacting the object (Table 4), strongly suggesting that they used visual feedback ‘in flight’ in an attempt to correct reach and grasp programming errors. The children with amblyopia also programmed their PG to occur later in the movement and much longer after PD of the reach (Table 3), this loss of normal coupling (p=0.007) often resulting in pre-shaping of the grasp while their hand was moving slowly near the target (Fig.9). This slower approach to the objects probably accounted for their consistently smaller peak grip apertures (p=0.012) – rather than indicating improved grip scaling for target size – since there was less need for them to increase the safety margin by opening their hand wider during this time.

Although the absence of any view x subject-type interactions suggested that the deficits among the amblyopic children occurred across all views, because of the surprising implication that this even applied to their dominant eye alone, we examined the differences further, by comparing between-group performance under each separate viewing condition. One-way ANOVA revealed significant impairments affecting all 13 parameters (as described above) in the amblyopic subjects with both eyes open, but with slightly fewer differences for the monocular comparisons (see Tables 3 & 4 for details). For the fellow (amblyopes) versus dominant (control) eyes, the amblyopic children performed worse on 10 of the 13 parameters, but with no statistical difference in occurrence of the error-types involving spatial path corrections before (p=0.13) or after (p=0.24) object contact or of post-contact grip adjustments (p=0.24). Nine measures were significantly different for the amblyopic versus non-dominant eyes with more similarities in grasp parameters than with binocular vision, again including adjustments with a spatial path element before (p=0.14) or after (p=0.054) contact. Thus poorer performance of the children with amblyopia was most marked under habitual, binocular viewing, in which their stereo sensitivity was reduced or absent compared to the control subjects with normal binocularity, whereas deficits in their fellow and amblyopic eye performance were mainly related to measures of the movement dynamics rather than accuracy (e.g., spatial errors). Moreover, contrary to expectation, performance when using the amblyopic eye alone was not significantly worse on any of the 20 parameters examined in the patients with moderate-to-severe compared to mild VA loss (One-way ANOVA, all p>0.1).

[Figure 10, near here]

Effects of amblyopia severity and cause

Further comparisons were made between the normal and amblyopic children, grouped according to their IOD (none, mild, moderate/severe) or SA (normal, coarse, negative) to determine whether either of the two factors was related to the amblyopes' reaching and grasping deficits. Significant differences in some of the movement kinematics (Table 3) were found between the controls and children with moderate-to-severe IOD or with no measurable stereovision, while the performance of those with mild amblyopia or coarse stereopsis tended to be intermediate between the two extremes – though not significantly different from either of them – so that there was no clear distinction between the effects of reduced visual versus stereo acuity on performance. Increases in corrections to the reach trajectory and grip positions occurring before object contact and in cumulative post-contact grasping errors, however, correlated more with worsening stereo acuity than IOD (Table 4). These different relationships are illustrated in Figure 10 for total grasping error-rates. The control subjects made significantly fewer errors than the patients irrespective of whether their amblyopia was mild ($p=0.014$) or moderate-to-severe ($p=0.011$), whereas error-rates were greatest among those with negative stereovision ($p<0.001$) but comparable to the controls in the patients possessing coarse stereopsis ($p=0.1$). These outcomes survived the removal from the data sets of the 3 subjects in the coarse stereo-group who had SA thresholds in the normal range and mild amblyopia (Table 2), showing that their inclusion was not solely responsible for the effects.

We also examined whether there were differences in the main movement parameters related to the cause of the patients' amblyopia. There were no main effects, but there was a significant view x cause interaction for total grasping error-rates ($F_{(2,38)}=4.3$, $p=0.021$), attributable to a tendency of the children with manifest squint (n=14) to make more errors when using both eyes and their dominant eye alone than those with 'pure' anisometropia (n=7). This result, however, is confounded by the fact that the strabismic subjects had poorer stereo (though better visual) acuity (Table 2).

Discussion

We present five main findings. (1) During normal development, performance on our task changed from predominantly feedforward control at ages 5-6, with children at ages 7-8 beginning to incorporate visual feedback mechanisms to guide their reach, and at 9-11 years also their grasp, so that their visuomotor behavior was almost equivalent to that of adult subjects. (2) The importance of binocular stereovision for improving movement programming and guidance increased in parallel with these developmental changes, providing adult-like benefits for performance only in the oldest children. (3) The movements of children with amblyopia were generally slower and poorly controlled compared to their age-matched peers with normal vision. (4) These deficits occurred not only under binocular and amblyopic eye viewing conditions, but also when patients used their dominant eye alone. (5) The presence of low-grade (coarse) binocular stereovision, nonetheless, provided some benefits for performance.

The reaching and grasping of the youngest group of children tested here showed some binocular advantages for movement preparation (Figs. 4 & 5). These probably arose from more reliable spatial information, than when viewing monocularly, about the 3D properties (position, size, shape) of the target object, and so may have improved advance planning of where best to make initial contact with the thumb- and finger-tips for grip stability. But they showed little evidence that on-line guidance was subsequently exploited to optimize performance. This and the signs that our middle children used visual feedback for controlling the reach are in broad agreement with previous work[19-22] indicating that ages 7-8 represent a transitional stage between the earlier ballistic and later more integrated approaches adopted at 9-11 years of age. Our finding of few binocular advantages among 5-6 year olds, increasing toward adult levels in these older children, especially for feedback control, confirms and extends earlier work by Watt et al (2003)[29] who examined fewer movement parameters than we did and did not test children in the transitional (7-8 year) age-range. We can also exclude the possibility that general improvements in vision were responsible for these childhood progressions, because participants in our early, middle and late age-groups had similar visual and stereo acuities (Table 1), although these were both significantly better in the adult subjects and so may have contributed to aspects of their faster and more accurate performance.

Use of sensory feedback to modify or adapt movements on-line is demanding of neural resources, as the information required has to be readily accessible, reliable and rapidly assimilated. Fast processing of binocular disparity cues related to depth changes between the moving hand/finger-tips and the stable grasp-points on the target object satisfy these requirements, since recovery of this information by adults using only monocular depth cues is slower[31] and lacks certainty[1-6]. It may be that normal 5-6 year old children are able to successfully combine static disparate inputs from the two eyes for movement planning and programming, but have not acquired a full capacity to integrate dynamic binocular cues for on-line control required to guide their hand movements-in-progress, and so do not generally attempt to correct its in-flight approach velocity, except – occasionally (Fig.6B) – in the last moments before contact[19]. Other existing evidence supports this possibility. Like adult subjects[3,5], normal children aged 7 years and above slow their reach and widen their grip (to increase the safety margin) when they cannot see their moving hand or the goal object after movement onset[20,22], effects consistent with a fast and continuous monitoring of depth changes between the hand and target via visual feedback, when this is available, during the final approach. By contrast, 5-6 year olds appear to be affected only when the target is invisible[20], but not by selectively removing sight of their hand[22]. This dissociation suggests that when they do use feedback, its main purpose is to up-date their internal representations of the target's spatial properties originally computed before they start moving, rather than for assimilating on-going changes in hand-target depth.

Our previous work on adults with persistent amblyopia[12] revealed major deficits in affected eye compared to binocular and dominant eye performance in the sub-group with moderate-to-severe, but not mild, VA loss. In our amblyopic children, however, differential effects of using the affected eye were less pronounced (Tables 3 & 4) and independent of the degree of amblyopia present. While classification of these sub-groups was based on the absolute acuity loss in the affected eye in the adult study but on the IOD in the present one, this change in criteria does not account for the different findings, because only two of the more affected children would have been re-classed as 'mild' amblyopes according to the previous scheme.

Instead, it arose because the binocular – and even the better eye – performance of the children with amblyopia were so much poorer than the control group. Although they were able to appropriately scale their reach and grasp to changes in the target's location or size between trials, the times spent undertaking the whole movement, decelerating towards and grasping the object were all greatly increased, consistent with uncertainties about these precise object properties at the movement planning stage. Their maximal hand opening also occurred while it was moving slowly in advance of object contact, so providing extra time to make overt corrections for errors in their reach direction and digit positions during grip closure, these latter arising with similar frequency whichever eye(s) were being used (Table 4), although more commonly, compared to control children, with binocular viewing. Nonetheless, they still had to make more post-contact adjustments to their grasp than normal, and always made longer contacts with the object before lifting it. These post-contact effects may represent costs of defective visual guidance, by ensuring via tactile and/or proprioceptive feedback, that it could be safely picked up.

The fact that the severity of several of the deficits (e.g., Fig.10) in the amblyopic children correlated more with their reduced grade of binocular stereovision than with the visual acuity loss in their affected eye, supports the conclusion that their abnormal binocularity was the main responsible factor. Indeed, the same conclusion has been drawn from related studies showing that reduced stereovision has a more detrimental effect than VA loss on the time-limited completion of other visuo-manual tasks (e.g., beading-threading, peg-in-board placing, copy-drawing) in children with amblyopia[32-34]. It is thus becoming increasingly clear that the development of movement control and coordination is impaired in children with abnormal binocular vision. Our present behavioural analyses suggest that they attempt to compensate for movement programming errors by using degraded visual feedback – rather unsuccessfully – and subsequent non-visual feedback to rectify the problems. Our analyses were, however, inferential and so it is unclear whether their unsuccessful use of vision for on-line guidance resulted from defective up-dating of already flawed target information, from difficulties in monitoring changes in hand-target depth during the movement or from a combination of the two. Formal assessment of these possibilities would require comparing the effects of 'no vision' conditions in which either the target or their hand becomes invisible at movement onset, as has been done in normal subjects[3,5,20,22] but not yet, to our knowledge, in children or adults with amblyopia. Whether amblyopic children try to further compensate for their visual impairments by spending more time preparing their movements prior to onset also remains unclear, because we were unable to assess their reaction times in the present study. These issues clearly warrant future investigation.

Either way, their approach differed markedly from children with developmentally-normal binocularity. We hypothesize that their deficits likely arise from dysfunction of dorsal stream areas involved in processing information for the control of hand actions[25-27] and in which structural abnormalities have been described in children[28] and adults[35] lacking binocular stereopsis. One of these latter is a region of the lateral occipito-parietal cortex, probably containing areas V3A and V7[28], which normally exhibit particularly strong activations to stereoscopic stimuli (even at threshold)[36,37] containing real depth structure mediated by selectivities for absolute and metric disparity processing[38-40], and which feed (higher) anterior intraparietal (AIP) areas directly concerned with precision grasping of 3D objects[25,26,41-43]. Another involves regions of superior parieto-occipital cortex (SPOC), putatively including area V6A[28,35], which shows a mixture of visual-somatosensory near-space representations[44,45] for encoding reach goals during hand transport[43, 46,47].

Full depth perception, however, is usually achieved by combining binocular disparity with various monocular cues, one of which, motion parallax derived from head motion, is a fast and automatic source of depth information. We did not restrict our subjects' head movements, so they were free to exploit this and other potential monocular (e.g., pictorial) depth cues, as they may have done when executing everyday visuomotor tasks for years previously. The fact that the children with amblyopia still performed poorly clearly suggests that the availability of such cues were insufficient to normalize their movements. Moreover, it is unlikely that their performance would have improved had we explicitly encouraged them to generate head movements, because previous work has shown that amblyopes are equally impaired when attempting to use binocular disparity or motion parallax cues for depth discrimination[48.] It has also been shown that adults with long-term mono-vision, due to removal of one eye earlier in life, do produce more head motion when reaching-to-grasp objects, yet their movements are just as slow as those of normal subjects forced to temporarily use one eye[49].

Interestingly, the performance of the amblyopic children also differed from that of adults with persistent amblyopia[12] or more selective stereo-deficiency[13] on our same task. Adults with these disorders tend to be less reliant on visual guidance during the in-flight approach to the target and more on later non-visual feedback to modify and stabilize their grip on the object during its manipulation. Moreover, use of their dominant eye is quite similar to that of normal adults, whereas the amblyopic children studied here were significantly impaired, relative to age-matched peers, on most measures of performance dynamics when using their fellow/better eye. While a few statistically significant deficits in contrast and alignment sensitivity have been reported for dominant eye viewing among some amblyopic subjects, these are typically minor[50-52] and related to aspects of vision of little obvious relevance to our task employing solid, high-contrast objects. We did not assess these thresholds in the present study, but we did measure monocular letter acuities and all non-amblyopic eyes were found to be within normal limits (Tables 1 & 2). These considerations suggest that developmental deficits in binocular reaching and grasping abilities in amblyopia initially generalize to the dominant eye as well, with performance under both viewing conditions showing adaptations later in life.

This generalization to the dominant eye is, perhaps, our most unanticipated finding. It is also of considerable clinical relevance, since the majority of strabismic – and many aniosmetropic – amblyopes rely mainly on their fellow eye in everyday living, as vision in the amblyopic eye is completely or partially suppressed. The impaired dominant eye performance, relative to control subjects, of children with either type of amblyopia thus implies that they will be notably disadvantaged in habitual daily activities requiring close coordination between the eye(s) and hand. Evidence further implies that abnormal binocularity may affect their educational attainment, as reading speeds with both eyes open are significantly slower than normal in microstrabismic children with reduced stereo acuity[53]. Indeed, recent evidence[54] indicates that this problem may be worse in adult strabismics lacking measurable stereopsis and that, in these cases, the reading impairment affects the fixing eye as well and is associated with abnormalities in its movement, manifest by longer fixations and more backward (regressive) saccades between successive text characters.

Abnormalities in fixation, fusional vergence and saccades are known to occur in adult strabismics[54-57] and it has now been reported that anisometropes make more corrections than adults with normal vision when making saccades with their dominant eye to targets that are the goal of manual pointing movements[58]. These findings together[55-58] raise the question of whether inaccurate, visually-cued eye movements, which may also be a consequence of parietal eye field abnormalities[59] in amblyopia[35,60], contribute to the hand movement deficits we describe. While reaching-to-grasp solid objects, adults with normal vision fixate continually on the target[61] with strong indications that their gaze becomes selectively directed towards either the thumb- or the finger-contact sites in the final approach, to enhance on-line visual guidance of the leading digit[62-64]. If amblyopic children also have generalized defects in directing their gaze – for example, by making multiple corrective saccades and fixations while their hand moves towards the object – this could interfere with their ability to monitor changes in its depth relative to the target and so contribute to their slower approach dynamics across all viewing conditions, including with their fellow eye. This is a possibility that deserves further investigation. But since the eye movement defects discussed so far have been established in adult amblyopia, they cannot obviously account for the subsequent age-related adaptation of binocular and fellow eye performance on our task.

Our findings confirm previous evidence[19-22,29] that the normal maturation of eye-hand coordination skills is protracted, and probably not fully complete until well into the teenage years, so that our amblyopic children were at an age equivalent to about half-way through this process. Motor skill acquisition usually proceeds by trial and error-correction, in which cognitive demands are placed upon attending to intrinsic sensory feedback derived from the movement itself and to more consciously-accessible extrinsic feedback (including from explicit retrospective instruction) regarding errors and their potential cost, in order to enhance memorial representations for improving future action planning. Developmental research on visuomotor control[19,20,22] and learning[21,65] has shown that normal children benefit from all these types of feedback from the age 7-8 onwards, when they are also more open to instructional feedback than young adults[65]. We, therefore, suspect that longer-term reach-to-grasp adaptations in amblyopic subjects likely emerges during the second decade of life through the implementation of a more efficient motor planning strategy that deliberately minimizes in-flight movement execution times and guidance during binocular viewing, and which transfers to the dominant eye when this also happens to be the habitual state (due to suppression of the amblyopic eye) or, as here, when vision is artificially restricted to it.

Taken altogether, these considerations further suggest that partial recovery of reach-to-grasp deficits may be accelerated by treatments that promote the restoration of binocularity in childhood strabismic and anisometropic amblyopia. Conventional therapy consists of refractive correction usually followed by part-time occlusion of the non-amblyopic eye, which can lead to marked improvements in stereo acuity, except in cases of large-angle squint[66]. Even this remains feasible, however, because some children can recover stereovision after squint surgery, suggesting that the neural mechanisms underpinning normal binocularity are present, but functionally suppressed[67,68]. We plan to examine whether binocular recovery mediated by these conventional treatments has immediate benefits for eye-hand coordination, along with some of the other questions raised by this preliminary work, via longitudinal study of larger cohorts of children undergoing clinical management for different types and depths of amblyopia.

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Figure Legends

Figure 1. The experimental workspace (not to scale). Subjects sat gripping the midline 3 cm diameter start button (large black circle). On different trials they reached to objects at one of three positions at different distances from the start button (small numbered circles): 'near' along the midline or 'far' to either the right or left (which would be into ipsi-space and contra-space, respectively, for a right-handed subject). Early children generally reached to the two shortest distances (12, 20 cm; open circles), middle children to intermediate distances (18, 30 cm; grey circles) and late children and adults to the furthest distances (25, 40 cm; black circles) in accordance with their different arm lengths.

Figure 2. Adult-like (A) velocity profile and (B) grip aperture profile of well-executed binocular movements performed by normal 10-year old subjects, and showing some key landmarks used in the kinematic analyses. The cue to move occurred at time 0 msecs, with the reaction time (RT) to movement onset (left-most vertical dotted line) at (A) ~500 msecs and (B) ~650 msecs. (A) The moments of peak velocity (PV) and peak deceleration (PD, filled circle) in the reach and of initial object contact (OC, open circle) are indicated, with arrows between the dotted lines showing the time to PD (ttPD) after movement onset and the low velocity phase (LVP) of the reach between PD and OC. (B) The moments of peak grip (PG), object contact (OC) and the movement end-point (right-most dotted line) are indicated, with arrows between the dotted lines showing the time to PG (ttPG) after movement onset, the grip closure time (GCT) between PG and OC, and the grip application time (GAT) after OC.

Figure 3: Median percentages of total movement duration spent in the low velocity phase (LVP) of the reach and in the grip closure time (GCT) as a function of age. Early, 5-6 year olds; Middle, 7-8 year olds; Late, 9-11 year olds. Asterisks indicate significant differences compared to adult performance. Error bars, SEM.

Figure 4: Mean peak reaching velocity scaling to midline-near (M,Near), ipsilateral-far (I,Far) and contralateral-far (C,Far) target positions as a function of age and binocular (open circles)

versus monocular (dominant eye, filled circles) viewing conditions. Early, 5-6 year olds; Middle, 7-8 year olds; Late, 9-11 year olds. Error bars, SEM.

Figure 5: Mean peak grip aperture scaling to small and large object sizes as a function of age and viewing condition. Other conventions are as Fig.4.

Figure 6: Mean (A) collision, (B) pre-contact reach velocity and (C) post-contact grasping error-rates as a function of age and binocular (unfilled bars) and monocular (dominant eye, filled bars) viewing conditions. Early, 5-6 year olds; Middle, 7-8 year olds; Late, 9-11 year olds. Asterisks indicate significant binocular advantages. **(For indications of variability, see Supplementary Table S3).**

Figure 7: Median (left) final approach times in the low velocity phase of the reach and (right) grip application times during object manipulation in control and amblyopic children under each viewing condition. Error bars, SEM.

Figure 8: Velocity profiles obtained on equivalent binocular trials in children at age 6 with (A) normal vision and (B) moderate-to-severe anisometropic amblyopia and marked (negative) stereovision loss. Conventions are as in Fig.2A, with moments of PD and OC indicated by the filled and open circles, respectively. The normal child collided with the goal object, having contacted it before the point of PD, resulting in a negative value for the LVP of his reach, whereas this period was markedly extended (to over 1000 msecs) in the amblyopic child, who also made multiple corrections in hand velocity before and after object contact (arrows).

Figure 9: Grip aperture profiles obtained on equivalent binocular trials in children at age 6 with (A) normal vision and (B) moderate-to-severe anisometropic amblyopia and marked (negative) stereovision loss. Conventions are as in Fig.2B. The normal child spent very little time (~67 ms) closing his grip and in contact (~33 ms) with the object before lifting it, whereas grip closure and application times were markedly extended (to over almost 1500 ms in total) in the amblyopic child, who also made adjustments in his digit positions just before and after object (arrows).

Figure 10: Differences in grasping error-rates between children with normal vision (controls) and with amblyopia, sub-divided by their deficits in visual acuity (mild, mod/severe) or in stereo acuity (coarse, negative), as a function of binocular (open bars), fellow/dominant eye (grey bars) and affected/non-dominant eye (filled bars) viewing conditions. Error bars, SEM.

Figure 1:

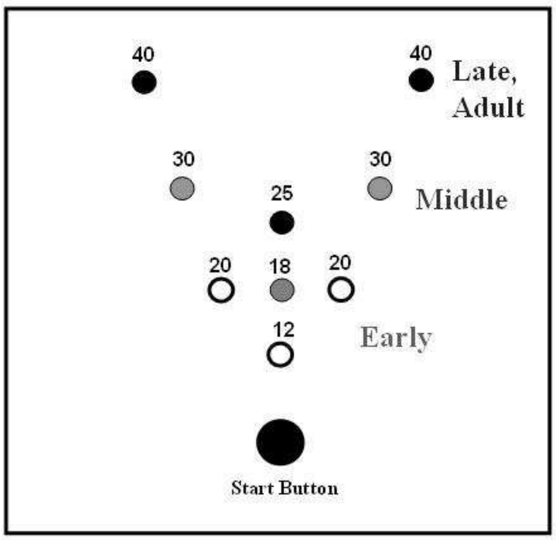

Figure 2:

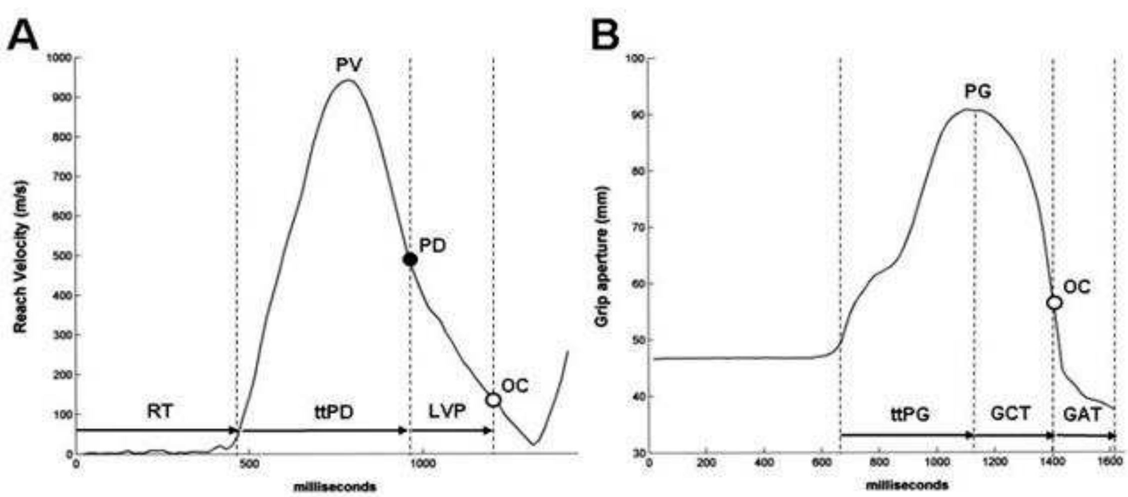

Figure 3:

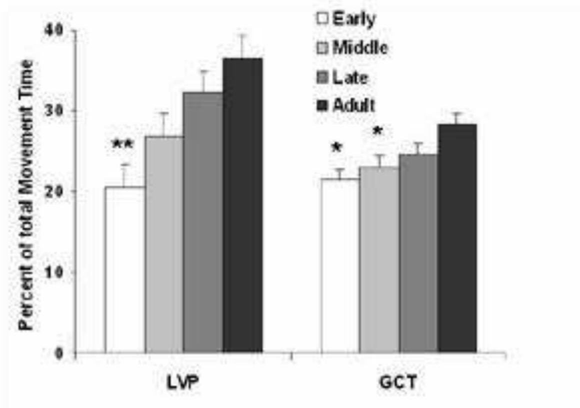

Figure 4:

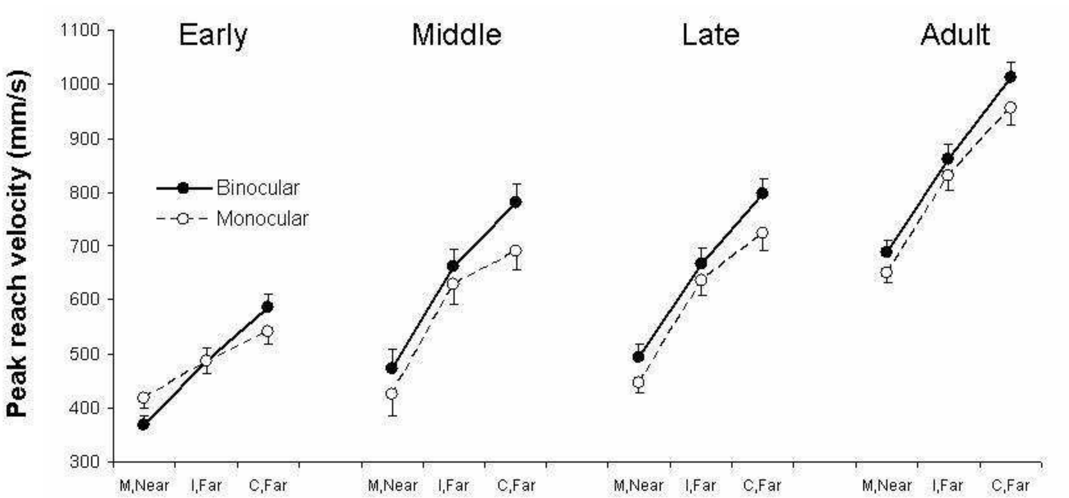

Figure 5:

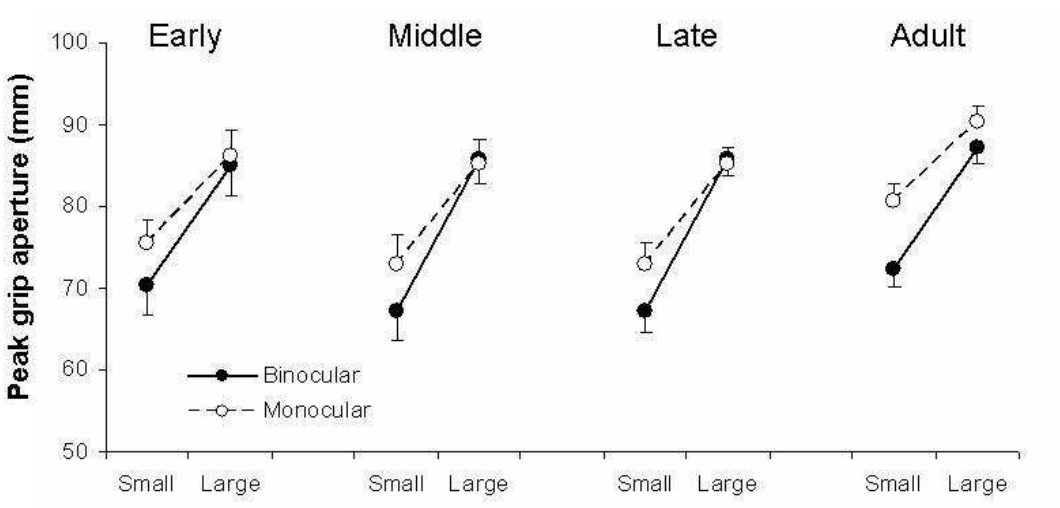

Figure 6:

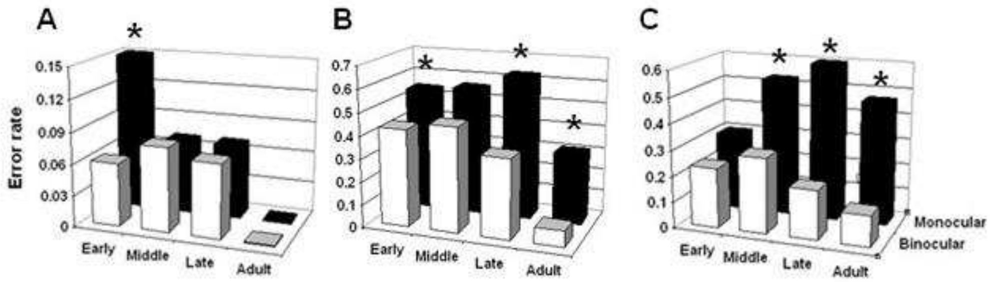

Figure 7:

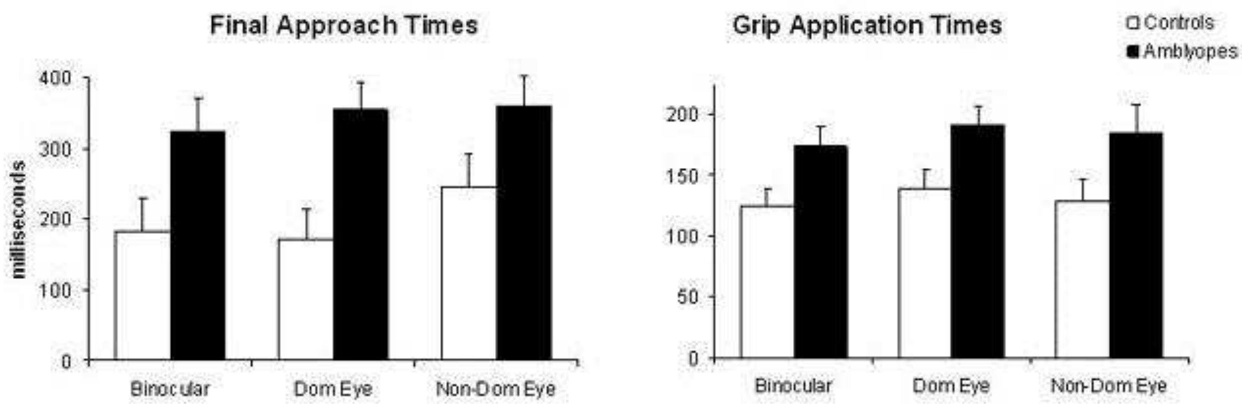

Figure 8:

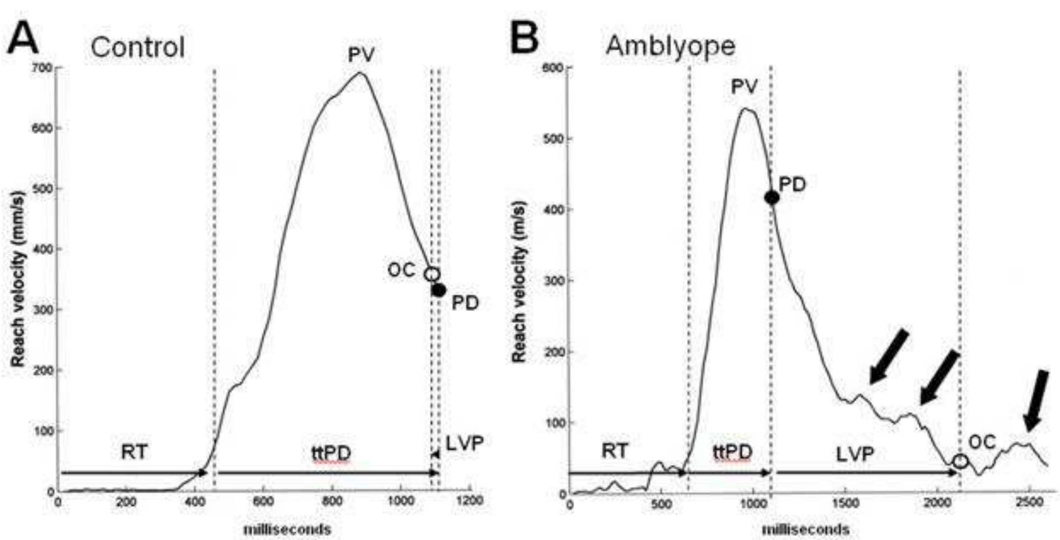

Figure 9:

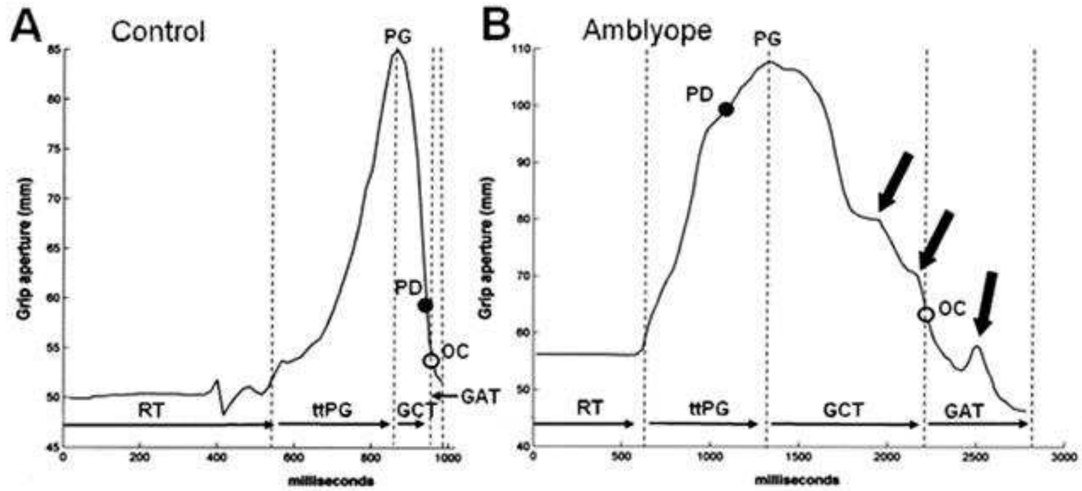

Figure 10:

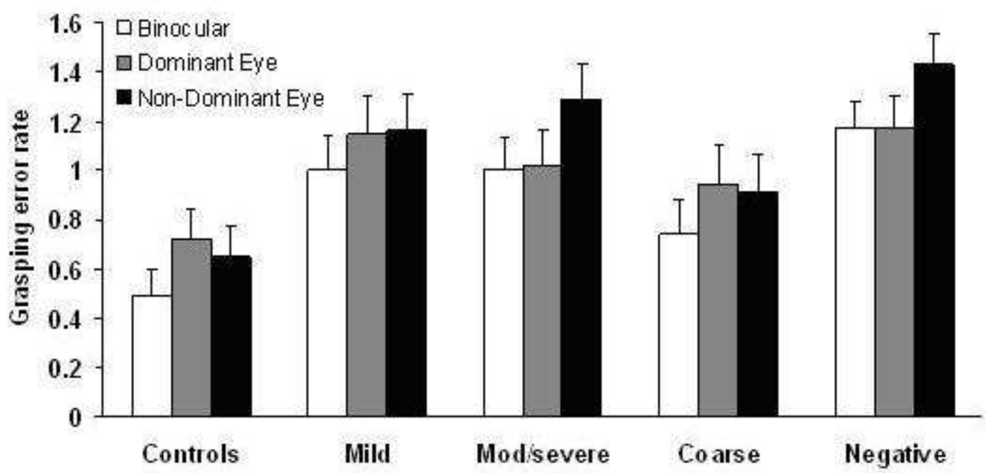

Table 1. Mean (±SD) binocular, dominant (DOM) and non-dominant (N-D) eye visual acuity (VA) and stereo acuities of the groups of normal child and adult participants

Group	Age (years)	logMar VA Binocular	logMar VA Dom Eye	logMar VA N-D Eye	Inter-Ocular Difference	Stereo acuity (arc secs) Crossed,	Uncrossed
Early (n=11)	6.4 (±0.4)	0.01 (±0.05)	0.06 (±0.07)	0.08 (±0.06)	0.05 (±0.04)	45 (±13),	57 (±21)
Middle (n=11)	8.2 (±0.4)	-0.02 (±0.07)	0.04 (±0.08)	0.02 (±0.07)	0.04 (±0.04)	44 (±24),	63 (±28)
Late (n=14)	10.3 (±0.5)	-0.06 (±0.06)	0.01 (±0.08)	0.03 (±0.08)	0.04 (±0.03)	51 (±15),	50 (±19)
Adults (n=11)	25.3 (±9.2)	-0.14 (±0.08)	-0.07 (±0.07)	-0.05 (±0.07)	0.04 (±0.02)	33 (±11),	31 (±11)

Table 2: Patient details

Subject	Age (years)	Acuity (logMAR)		IOD	Severity	Refraction		SA (arc secs)	Cause
		R	L			R	L		
1	4.7	0.1	0.3	0.2	Mild	+6.00	+5.50	3000”	S
2	5.0	0.1	0.22	0.12	Mild	+6.00	+7.00	N	S
3	5.9	0.32	0.04	0.28	Mild	+5.50/-1.50x180	+4.00/-1.00x180	N	S
4	6.0	0.0	0.14	0.14	Mild	+6.50/-1.00x100	+7.25/-0.75x90	200"	S
5	6.1	0.3	0.1	0.2	Mild	+4.50/-0.75x180	+4.50/-0.25x180	N	S
6	6.1	0.1	0.34	0.24	Mild	+3.50/-1.00x180	+4.00/-1.00x180	N	S
7	6.5	0.0	0.12	0.12	Mild	+2.50/-0.75x25	+2.75/-0.50x5	170"	S
8	6.6	0.06	0.26	0.2	Mild	+6.00/1.25x5	+7.25/-1.50X5	3000”	S
9	7.2	0.0	0.16	0.16	Mild	+1.00/-1.25x100	-2.25/-1.50x95	85"	A
10	8.3	0.04	0.32	0.28	Mild	+0.50/-0.50x180	plano/-2.00x170	55"	A
11	4.5	0.06	0.8	0.74	Mod/Sev	+0.50	+2.00/-1.50x180	N	S+A
12	5.6	0.08	0.44	0.36	Mod/Sev	+2.00/-0.50x10	+2.50/-1.00x170	N	S
13	5.8	-0.1	0.76	0.86	Mod/Sev	+1.00/-0.25x180	+7.25/-2.25x12.5	N	A
14	6.0	0.0	1.1	1.1	Mod/Sev	+4.25/-0.50x180	+4.75/-1.25x180	N	S
15	6.1	0.0	0.62	0.62	Mod/Sev	+1.00/-0.25x180	-8.00/-0.50x30	N	A
16	6.4	0.02	0.56	0.54	Mod/Sev	+2.00/-2.50x180	-5.00/-4.00x180	N	A
17	6.4	0.8	0.02	0.78	Mod/Sev	-9.00/-2.50x40	-4.00/-2.00x140	200"	S+A
18	6.8	0.68	0.04	0.64	Mod/Sev	-4.50/-0.75x10	-0.25/-0.75x150	85"	A
19	7.0	0.9	0.2	0.7	Mod/Sev	-7.00/-2.75x10	+0.25/-0.25x180	400"	S+A
20	8.1	1.0	-0.1	1.1	Mod/Sev	+3.50/-0.50x90	plano	N	A
21	8.2	0.42	-0.14	0.56	Mod/Sev	+4.25	+4.25/-0.50x180	100"	S

Key: IOD, interocular acuity difference. Amblyopia severity: Mild (IOD 0.1-0.3); Mod/sev, moderate to severe (IOD >0.31). SA, stereoacuity; N = negative, none measurable. Cause: S, strabismus; A, anisometropia; S+A, strabismus and anisometropia.

Table 3. Median (± SEM) reach and grasp kinematics by subject type and viewing condition

Parameter	**Control** Binocular	Dom Eye	ND Eye	**Amblyopia** Binocular	Dom Eye	ND Eye	**Control versus Amblyopia** (% difference)	$F_{(1,34)}$	**By Visual Acuity loss** $F_{(2,33)}$	**By Stereo Acuity loss** $F_{(2,33)}$
Movement Time (ms)	833 ± 34	912 ± 61	912 ± 57	1056 ± 66#	1122 ± 45#	1118 ± 52#	(+24%)	**p=0.008**	**p=0.025**	**p=0.028**
Reaching:										
Peak Velocity (mm/s)	528 ± 34	492 ± 35	506 ± 32	579 ± 25	549 ± 28	**537 ± 25***	(+9%)	p=0.25 NS	p=0.4 NS	p=0.06 NS
Reach Duration (ms)	704 ± 27	737 ± 36	758 ± 42	844 ± 52#	877 ± 43#	889 ± 46#	(+19%)	**p=0.021**	**p=0.042**	**p=0.045**
Time to Peak Dec (ms)	509 ± 20	514 ± 26	469 ± 16	511 ± 21	512 ± 26	512 ± 22	(+3%)	p=0.6 NS	p=0.7 NS	p=0.7 NS
Low Velocity Phase (ms)	182 ± 32	173 ± 31	246 ± 33	326 ± 47#	355 ± 38#	364 ± 42#	(+73%)	**p=0.007**	**p=0.019**	**p=0.027**
Grasping:										
Peak Grip Aperture (mm)	78 ± 2	81 ± 2	82 ± 2	73 ± 2#	75 ± 2	75 ± 2#	(-1%)	**p=0.012**	**p=0.031**	**p=0.043**
Grip Size at Contact (mm)	52 ± 2	**58 ± 2****	**59 ± 3****	51 ± 1	54 ± 1	**57 ± 2****	(-1%)	p=0.25 NS	p=0.2 NS	p=0.5 NS
Time to Peak Grip (ms)	509 ± 21	531 ± 29	514 ± 26	588 ± 38#	603 ± 26#	**654 ± 34*#**	(+19%)	**p=0.019**	**p=0.048**	p=0.06 NS
Grip Closure Time (ms)	172 ± 14	185 ± 17	196 ± 22	237 ± 20#	251 ± 21#	244 ± 28	(+32%)	**p=0.033**	p=0.08 NS	p=0.08 NS
Grip Application Time (ms)	125 ± 14	140 ± 14	129 ± 17	174 ± 16#	192 ± 15#	185 ± 23#	(+40%)	**p=0.02**	p=0.054 NS	p=0.07 NS
Reach-Grasp Coupling										
Peak Dec-to-Peak Grip (ms)	0 ± 23	7 ± 23	34 ± 23	66 ± 25#	88 ± 19#	95 ± 21	(+507%)	**p=0.007**	**p=0.024**	**p=0.026**
At Object Contact (ms)	61 ± 7	63 ± 6	60 ± 8	70 ± 8	75 ± 5	85 ± 9	(+85%)	p=0.1 NS	p=0.08 NS	p=0.08 NS

KEY: DOM, dominant; ND, non-dominant. Values given in bold under the monocular conditions were significantly different to binocular viewing: *$p<0.05$; **$p<0.01$. Values followed by # in the amblyopia group were significantly different (1-way ANOVA) from the equivalent control data for the same viewing condition. % difference refers to overall median performance across all 3 viewing conditions. NS, not significant.

Table 4. Mean (± SEM) reach and grasp error-rates by subject type and viewing condition

	Control			Amblyopia			Control versus Amblyopia Group		By Visual Acuity loss	By Stereo Acuity loss
Parameter	Binocular	Dom Eye	ND Eye	Binocular	Dom Eye	ND Eye	(% difference)	$F_{(1,34)}$	$F_{(2,33)}$	$F_{(2,33)}$
Reaching:										
Pre-Contact Velocity corrections	0.34 ± 0.18	**0.40 ± 0.15***	**0.49 ± 0.13***	0.49 ± 0.27	0.48 ± 0.23	0.50 ± 0.27	(+20%)	p=0.2 NS	p=0.4 NS	p=0.06 NS
Pre-Contact Spatial Path corrections	0.13 ± 0.15	0.24 ± 0.23	0.22 ± 0.2	0.28 ± 0.18#	0.33 ± 0.21	0.36 ± 0.22#	(+64%)	**p=0.009**	**p=0.034**	**p=0.002**
Collisions	0.04 ± 0.09	**0.13 ± 0.13***	**0.11 ± 0.14***	0.03 ± 0.06	**0.07 ± 0.09***	**0.08 ± 0.09***	(-36%)	p=0.2 NS	p=0.3 NS	p=0.3 NS
Grasping:										
Pre-Contact Grip adjustments	0.03 ± 0.08	0.04 ± 0.06	0.08 ± 0.1	0.18 ± 0.18#	0.15 ± 0.14#	0.15 ± 0.17	(+220%)	**p=0.006**	**p=0.021**	**p=0.007**
Post-Contact Velocity or Spatial Path corrections	0.09 ± 0.11	0.16 ± 0.16	0.16 ± 0.14	0.25 ± 0.15#	0.24 ± 0.16	0.25 ± 0.16	(+80%)	**p=0.022**	p=0.075 NS	**p=0.045**
Post-Contact Grip adjustments	0.05± 0.06	0.11 ± 0.1	0.07± 0.08	0.10 ± 0.12#	**0.16 ± 0.14***	**0.16 ± 0.13*#**	(+83%)	**p=0.041**	p=0.1 NS	p=0.07 NS
Wide initial contacts	0.20 ± 0.11	0.25 ± 0.13	0.26 ± 0.1	0.26 ± 0.13	0.27 ± 0.14	**0.34 ± 0.18***	(+20%)	p=0.1 NS	p=0.3 NS	**p=0.03**
Prolonged contacts	0.07 ± 0.09	0.06 ± 0.09	0.07 ± 0.1	0.19 ± 0.17#	0.16 ± 0.14#	0.20 ± 0.13#	(+175%)	**p=0.001**	**p=0.003**	**p=0.006**

KEY: DOM, dominant; ND, non-dominant. Values given in bold under the monocular conditions were significantly different compared to binocular viewing. *$p<0.05$. Values followed by # in the amblyopia group were significantly different (1-way ANOVA) from the equivalent control data for the same viewing condition. % difference refers to overall median performance across all 3 viewing conditions. NS, not significant.

Table S1. Trial sequences under each of the three blocked viewing conditions

Binocular Trial#	Object: Size, Position	Dom Eye Trial#	Object: Size, Position	Non-Dom Eye Trial #	Object: Size, Position
1	Small, Ipsi Far	1	Large, Midline	1	Large, Ipsi Far
2	Small, Contra Far	2	Small, Midline	2	Small, Contra Far
3	Large, Ipsi Far	3	Small, Contra Far	3	Small, Midline
4	Small, Midline	4	Small, Ipsi Far	4	Small, Ipsi Far
5	Large, Contra Far	5	Large, Contra Far	5	Large, Contra Far
6	Large, Midline	6	Large, Ipsi Far	6	Large, Midline
7	Large, Ipsi Far	7	Small, Ipsi Far	7	Small, Contra Far
8	Small, Contra Far	8	Small, Contra Far	8	Large, Contra Far
9	Small, Midline	9	Large, Ipsi Far	9	Small, Ipsi Far
10	Small, Ipsi Far	10	Small, Midline	10	Large, Ipsi Far
11	Large, Contra Far	11	Large, Contra Far	11	Small, Midline
12	Large, Midline	12	Large, Midline	12	Large, Midline
13	Large, Contra Far	13	Large, Ipsi Far	13	Large, Ipsi Far
14	Small, Contra Far	14	Small, Contra Far	14	Large, Contra Far
15	Small, Ipsi Far	15	Small, Midline	15	Large, Midline
16	Large, Ipsi Far	16	Small, Ipsi Far	16	Small, Ipsi Far
17	Large, Midline	17	Large, Contra Far	17	Small, Midline
18	Small, Midline	18	Large, Midline	18	Small, Contra Far

Table S2. Binocular advantages for median (± SEM) reach and grasp kinematics in normal children of different ages and in adult subjects

	EARLY			**MIDDLE**			**LATE**			**ADULT**		
Parameter	Binocular	DOM Eye	$F_{(1,10)}$	Binocular	DOM Eye	$F_{(1,10)}$	Binocular	DOM Eye	$F_{(1,13)}$	Binocular	DOM Eye	$F_{(1,13)}$
Reaction Time (ms)	869 ± 85	949 ± 98	**p=0.049**	839 ± 84	836 ± 78	p=1.0 NS	520 ± 15	606 ± 29	**p=0.01**	489 ± 28	524 ± 23	p=0.2 NS
Movement Time (ms)	833 ± 38	911 ± 61	p=0.2NS	841 ± 46	939 ± 45	**p<0.001**	855 ± 50	1026 ± 56	**p=0.001**	895 ± 24	1047 ± 47	**P=0.001**
Reaching:												
Peak Velocity (mm/s)	487 ± 36	465 ± 41	p=0.3 NS	662 ± 28	589 ± 34	**p=0.043**	664 ± 29	622 ± 27	**p=0.041**	882 ± 32	821 ± 32	**p=0.01**
Reach Duration (ms)	693 ± 28	740 ± 48	p=0.4 NS	712 ± 36	761 ± 32	**p=0.038**	729 ± 41	832 ± 34	**p=0.006**	760 ± 26	852 ± 41	**p=0.002**
Time to Peak Dec (ms)	500 ± 23	517 ± 34	p=0.6 NS	462 ± 24	477 ± 22	p=0.5 NS	458 ± 14	468 ± 16	p=0.5 NS	453 ± 17	464 ± 18	p=0.5 NS
Final Approach Time (ms)	173 ± 40	175 ± 39	p=1.0 NS	260 ± 37	236 ± 48	p=0.4 NS	263 ± 36	355 ± 26	**p=0.008**	301 ± 33	378 ± 30	**p=0.004**
Grasping:												
Peak Grip Aperture (mm)	78 ± 3	82 ± 3	**p=0.024**	77 ± 2	79 ± 2	p=0.2 NS	76 ± 2	80 ± 2	**p=0.027**	79 ± 3	86 ± 4	**p<0.001**
Grip at Contact (mm)	52 ± 2	58 ± 3	**p=0.01**	51 ± 3	54 ± 3	p=0.4 NS	52 ± 2	53 ± 2	p=0.7 NS	43 ± 1	46 ± 1	**p=0.01**
Time to Peak Grip (ms)	507 ± 22	526 ± 37	p=0.5 NS	503 ± 23	544 ± 26	p=0.1 NS	516 ± 16	546 ± 20	p=0.1 NS	524 ± 23	549 ± 26	p=0.2 NS
Grip Closure Time (ms)	166 ± 14	189 ± 21	p=0.2 NS	197 ± 18	207 ± 28	p=0.7 NS	202 ± 20	263 ± 20	**p=0.001**	236 ± 18	307 ± 24	**p<0.001**
Grip Application Time (ms)	137 ± 16	136 ± 16	p=0.9 NS	113 ± 14	145 ± 11	**p=0.023**	118 ± 11	171 ± 17	**p=0.003**	139 ± 7	182 ± 9	**p<0.001**
Reach-Grasp Coupling												
Peak Dec-to-Peak Grip (ms)	14 ± 21	37 ± 20	p=0.5 NS	46 ± 25	34 ± 26	p=0.6 NS	59 ± 12	90 ± 15	p=0.1 NS	64 ± 19	78 ± 13	**p=0.033**
At Contact (ms)	66 ± 9	58 ± 6	p=0.5 NS	51 ± 5	61 ± 9	p=0.3 NS	46 ± 4	75 ± 6	**p=0.001**	42 ± 5	83 ± 8	**p<0.001**

KEY: DOM; dominant. NS; not significant. Ages: Early (5-6 years); Middle (7-8 years); Late (9-11 years)

Table S3. Binocular advantages for mean (± SEM) reach and grasp error-rates in normal children of different ages and in adult subjects

	EARLY			**MIDDLE**			**LATE**			**ADULTS**		
Parameter	Binocular	DOM Eye	$F_{(1,10)}$	Binocular	DOM Eye	$F_{(1,10)}$	Binocular	DOM Eye	$F_{(1,13)}$	Binocular	DOM Eye	$F_{(1,10)}$
Reaching:												
Pre-Contact Velocity corrections	0.32 ± 0.05	0.42 ± 0.05	**p=0.045**	0.33 ± 0.07	0.37 ± 0.06	p=0.1	0.20 ± 0.05	0.34 ± 0.05	**p=0.033**	0.04 ± 0.01	0.19 ± 0.03	**p<0.001**
Pre-Contact Spatial Path corrections	0.09 ± 0.04	0.18 ± 0.06	p=0.1	0.09 ± 0.05	0.15 ± 0.04	p=0.2	0.10 ± 0.03	0.15 ± 0.04	p=0.1	0.01 ± 0.01	0.06 ± 0.01	**p=0.003**
Collisions	0.06 ± 0.03	0.15 ± 0.04	**p=0.02**	0.08 ± 0.03	0.07 ± 0.03	p=0.6	0.07 ± 0.02	0.07 ± 0.02	p=0.8	0.00 ± 0.00	0.00 ± 0.00	p=0.9
Grasping:												
Pre-Contact Grip adjustments	0.02 ± 0.02	0.04 ± 0.02	p=0.5	0.04 ± 0.03	0.04 ± 0.02	p=0.9	0.05 ± 0.02	0.14 ± 0.03	**p=0.004**	0.02 ± 0.01	0.06 ± 0.02	**p=0.016**
Post-Contact Velocity or Spatial Path corrections	0.11 ± 0.05	0.14 ± 0.04	p=0.5	0.19 ± 0.05	0.39 ± 0.07	**p=0.018**	0.09 ± 0.02	0.38 ± 0.05	**p<0.001**	0.03 ± 0.01	0.19 ± 0.03	**p<0.001**
Post-Contact Grip adjustments	0.05 ± 0.02	0.09 ± 0.03	p=0.1	0.04 ± 0.01	0.13 ± 0.03	**p=0.006**	0.05 ± 0.02	0.15 ± 0.02	**p=0.001**	0.04 ± 0.02	0.12 ± 0.03	**p=0.002**
Wide initial contacts	0.22 ± 0.03	0.25 ± 0.04	p=0.6	0.17 ± 0.03	0.28 ± 0.03	**p=0.037**	0.14 ± 0.03	0.19 ± 0.03	p=0.3	0.04 ± 0.01	0.09 ± 0.02	**p=0.013**
Prolonged contacts	0.07 ± 0.03	0.07 ± 0.03	p=0.9	0.06 ± 0.03	0.03 ± 0.02	p=0.2	0.05 ± 0.02	0.08 ± 0.02	p=0.4	0.05 ± 0.01	0.16 ± 0.03	**p<0.001**

KEY: DOM; dominant. NS; not significant. Ages: Early (5-6 years); Middle (7-8 years); Late (9-11 years)