Reach-to-Precision Grasp Deficits in Amblyopia: Effects of Object Contrast & Low Visibility

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Abstract

Adults with a history of unilateral amblyopia and abnormal binocularity have a range of visual deficits, with some of the ‘higher’ levels ones generalizing to their dominant (non-amblyopic) eye and linked to widespread binocular cortical network dysfunctions. Our interests are in how these problems also impact on their hand action control in real-world situations. We investigated whether eye-hand coordination deficits, known to exist in amblyopia when goal objects are presented under full-lighting and at high contrast, are exacerbated under low object-background contrast or in dim lighting/low visibility conditions. Hand movement parameters were recorded and quantified in 13 amblyopia and 13 control subjects while they reached-to-precision grasp objects using both eyes together or just their dominant or amblyopic/non-dominant eye alone under these 3 task conditions. Compared to controls, the amblyopia subjects spent significantly longer in preparing their movements, in the initial (planned) periods of their reach and grasp and in applying their grip, while making more reach and grasp errors under all 3 views and tasks. Deficits in planning and controlling the grasp were also *selectively* accentuated in the low contrast condition, but with no evidence of relatively worse performance under low environmental illumination. We suggest that the dysfunctions in amblyopia are associated with generalized difficulties in obtaining reliable visual evidence about the target’s 3D properties during movement planning and in selecting and guiding the proper course of action, especially when segregating the object from background is more challenging.

Keywords: eye-hand coordination, visuomotor control, strabismus, action planning

INTRODUCTION

Amblyopia is a common neurodevelopmental disorder characterized by reduced vision, usually in one eye, that cannot be immediately improved by optical correction. It results from abnormal binocular visual experience associated with the presence of image misalignment (due to strabismus), blur (from unequal refractive error/anisometropia) or deprivation (e.g., due to cataract), alone or in combination, in infancy or early childhood. Evidence suggests that the reduced vision that people with amblyopia encounter in their affected eye occurs along two major, independent dimensions (McKee et al., 2003); loss of spatial (e.g., letter) acuity and of contrast sensitivity, this latter being most evident at higher spatial scales, but often occurring at low spatial frequencies as well in all amblyopia sub-types (Hess & Howell, 1977; Levi & Harwerth, 1997, 1980). The visual acuity loss is used as the widely accepted clinical definition of the presence and severity of the disorder. Although there is evidence that losses occurring along a third major dimension, namely the presence or absence of binocularity (e.g., stereo acuity), is a better indicator of the overall visual status of both strabismic and non-strabismic amblyopia populations (McKee et al, 2003).

On the other hand, it is now also established that reduced amblyopic eye vision extends to certain grouping tasks based on the integration or segregation of signal from noise over quite wide regions of space, and which cannot be explained by the more ‘basic’ (i.e., first-order) losses in visual acuity and contrast detection present (for recent review, see Hamm et al., 2014). Some of these visual impairments in unilateral amblyopia – for example, in positional uncertainty/crowding (Levi & Klein, 1985) and in ‘global’ orientation, contour/shape and motion perception (e.g., Giaschi et al., 1992; Kovács et al., 2000; Wong et al., 2001; Mansouri et al., 2005; Simmers et al., 2003, 2005) – and in others with significant attentional-system demands (Sharma et al., 2000; Ho et al., 2006; Thiel & Sireteanu, 2009; Farzin & Norcia, 2011) have been shown to occur, if to a lesser extent, in the ‘normal’ (dominant or fellow/fixing) eye as well. This suggests that neurodevelopmental defects in amblyopia are not confined to ‘lower’ visual processing areas of calcarine (V1/V2) cortex, but extend to – and may be exacerbated in – the functional relations between extrastriate occipito-temporal (ventral) and occipito-parietal (dorsal) stream cortical networks. Growing evidence from neuroimaging studies supports this suggestion (Lerner et al., 2006; Li et al., 2007, 2011; Secen et al., 2011; Ding et al., 2013; for reviews, see Vida et al., 2012; Wong, 2012).

Nodes that are commonly implicated in these higher level dysfunctions include binocular regions of posterior parietal cortex, also generally associated with the programming and guidance of visually-guided actions (for recent review, see Goodale, 2011). Indeed, commensurate with this, a history of amblyopia and abnormal binocularity in both children and adults has recently been associated with slow and inaccurate performance, compared to matched developmentally-normal subjects, on a variety of everyday tasks requiring fine visuomotor control (for recent reviews, see Grant & Moseley, 2011; Wong, 2012; Birch, 2013). Of immediate relevance to the present study, specific performance deficits in relatively simple manual pointing (Niechwiej-Szwedo et al., 2011, 2012a, 2012b, 2014) or reach-to-precision grasping actions (Grant et al., 2007, 2014; Melmoth et al., 2009; Suttle et al., 2011) have been shown to include: (i) increased movement onset (i.e., planning/programming) times; and (ii) prolonged movement durations; mainly due to (iii) longer periods spent in the initial programmed phase of the movement (e.g., up to peak reach velocity or peak grip opening); with (iv) more corrections to the reach trajectory or digit positions during the later approach to the target; yet (v) terminating in more errors and loss of end-point accuracy. These deficits occur with habitual (i.e., both eyes open) and with amblyopic eye viewing, and even when using the dominant eye alone for some parameters mainly related to movement planning/programming. Moreover, their severity across all the 3 possible views – as on other fine visuomotor tasks (see Grant & Moseley, 2011; Birch, 2013) – usually correlates more with the patients' degree of binocular dysfunction than their visual acuity loss. It has been concluded from this that the defective binocular vision in amblyopia results in two general problems for motor control. First, it creates 'uncertainties' when attempting to encode the 3D spatial location and form/contour of target objects during movement planning, leading to impaired selection and programming of the hand actions directed towards them. Second, it impairs the use of subsequent visual feedback to correct these motor errors when attempting to guide the hand accurately to the target during movement execution.

By the term 'relatively simple' above, we mean that the deficits were revealed on tasks conducted under bright lighting with the hand directed to highly visible targets presented in structured environments containing many potential cues to distance and depth. However, in daily life, we are often required to interact with objects of low contrast relative to the background or in environments of low ambient illumination. Such low visibility situations have been shown to be more challenging for hand action control in normally-sighted adults (Churchill et al., 2000; Melmoth & Grant, 2012), resulting in slower movements accompanied by reduced end-point accuracy, analogous to the performance deficits of amblyopic adults under 'standard' high contrast conditions. Pardhan et al (2012) have also recently compared the performance during habitual viewing of older patients with marked central visual impairment affecting both eyes to that of age-matched controls on reach-to-precision grasps of high contrast *versus* low contrast or transparent 3D objects. The patients had prolonged movement onsets and durations, due to increased times to peak reach velocity and in grip closure during the guidance period, for the high contrast targets, and these indices of poorer performance were exacerbated – that is, deteriorated significantly more than in the controls – when the objects were of lower visibility. Reductions in binocular contrast sensitivity were more implicated in these effects than reduced visual acuity.

Against this background, we hypothesized that the greater demands imposed on the amblyopic visual system for encoding objects with low contrast or visibility would likely result in a similar exacerbation of their problems in hand action planning/programming and in error generation. More specifically, we predicted that their deficits in all aspects of movement timing and accuracy outlined above for high contrast objects should deteriorate much more on these harder tasks under all viewing conditions compared to the performance of control subjects, with the effects probably being more evident in non-binocular amblyopes with markedly reduced contrast sensitivity. The present study represents a preliminary test of these hypotheses, conducted on a sample of adult patients exhibiting a range of losses along the major dimensions of visual acuity, contrast sensitivity and binocularity.

MATERIALS & METHODS

2.1. Participants

Twenty six adult subjects took part in the study; 13 had a history of amblyopia and 13 were visually normal controls, matched by age (median = 23 years), gender (4 males, 9 females), sighting eye-dominance (6 right, 7 left) and hand-preference (12 right-handed patients, 11 right-handed controls), this latter information obtained from their responses to the short version of the Edinburgh inventory questionnaire (Oldfield, 1971). Participants were screened using standard clinical tests of (logMAR) visual acuity (VA), contrast sensitivity (CS), and binocularity, during which they wore any habitual refractive correction. VA was tested with both eyes open and with just the dominant (fellow/fixing/sighting) eye and non-dominant (affected/amblyopic/non-sighting) eye alone using a Bailey-Lovie chart held at 6 metres. CS, at a spatial frequency corresponding to ~ 1 cycle per degree (cpd), was also measured under each of these 3 views using the Pelli-Robson chart at a distance of 1 metre and test luminance ~64 cd/m^2. Assessments of binocularity included for suppression (Bagolini lenses); ocular alignment and motor fusion (cover test and prism fusion range); and stereo acuity (Wirt-Titmus test). All subjects gave informed consent to participate in the experiments, which were conducted in accord with the Declaration of Helsinki and with City University London ethical approval.

[Table 1, near here]

2.1.1. The subject's vision

Control subjects had no ocular disorders, other than refractive errors, and normal binocularity, with crossed stereo thresholds of at least 40 arc secs. Their average binocular, dominant eye and non-dominant eye logMAR VA was -0.14 (±0.09 sd), -0.07 (±0.14) and -0.03 (±0.14), respectively, with mean contrast sensitivities of 1.84 (±0.10), 1.71 (±0.08) and 1.71 (±0.09) under each of the 3 respective views. These latter are all at the lower end of normative values expected for adults in the age range (19-48 years) of our control participants (Mäntyjärvi & Laitinen, 2001). The likely explanation for this is that the luminance of the Pelli-Robson chart used was adapted to match to the normal lighting conditions of the hand movement testing laboratory (see below) and so was lower than that typically used in more formal clinical settings.

As summarized in Table 1, the amblyopia subjects comprised 6 with strabismus and 7 of mixed type (for 3 of whom – cases M3, M6, M7 – image degradation had probably been the main amblyogenic factor), but with the two sub-groups having similar distributions of visual loss along each of the 3 major dimensions. Average 'binocular' visual acuities among the 13 patients (-0.05 ±0.07 sd) were significantly worse (p=0.017) than the control subjects, as were those of their non-dominant (0.43 ±0.31 sd; p<0.001) – but not dominant (-0.03 ±0.08 sd; p=0.33) – eyes. Five of these cases (S1, S3, S4, M9, M13) also had contrast sensitivities in their non-dominant eyes that were worse than the lower limit (=1.60) found among our control subjects, even at the very low spatial frequency examined. Overall, though, there were no significant differences in mean CS at this spatial frequency in the patients under binocular (1.78 ±0.12 sd; p=0.33), dominant eye (1.74 ±0.13 sd; p=0.14) or non-dominant eye (1.58 ±0.15 sd; p=0.059) viewing compared to the controls, but with the latter trend towards a deficit reflecting the 'bi-modal' distribution of

CS loss in the amblyopia group. It should, finally, be noted that 2 of the cases (S1, M1) had interocular differences in VA of ≤0.10 log MAR and so would be classified as no longer amblyopic according to the accepted criterion of a 2-line difference between the two eyes. Indeed, their non-dominant eye acuities were within the range of our control subjects. We included them in the experiment because they both had complete suppression and failed the Titmus Fly test (at 3000 arc secs) resulting in their designation as being non-binocular or stereo 'Nil' (Table 1), with S1 also having reduced CS in his affected eye.

2.2. Hand movement recordings

General recording procedures were similar to those we used previously to examine hand action control in adults with amblyopia (e.g., Grant et al., 2007). The setup required participants to sit at a black table with the thumb and forefinger of their preferred hand gripping a 'start' button. This was a circular knob situated 12 cm from the table's edge, along the subject's midline and dictated the position of the digits before and at the end of each movement trial. Participants wore liquid-crystal containing goggles (Translucent Technologies, Montreal, Canada), which acted as a shutter system, with the lenses becoming suddenly transparent when a current was applied, but otherwise operating as opaque occluders. The goggles were programmed to follow a pseudo-randomised opening sequence which allowed the subject to view the workspace with both eyes together or with just their dominant or non-dominant eye alone on different trials. Subjects were instructed, on opening of the lens(es), to reach for the target 'as quickly, naturally and accurately, as possible', to precision grasp the object about halfway up using their thumb and forefinger, lift it and place it to one side, before returning their hand to the start position. To ensure that the instructions were understood and complied with, participants were given a few practice trials (usually 3 or 4 per view) under full lighting conditions and directed to cylindrical objects that were not used again later.

Movements of the subjects' preferred hand on each experimental trial were tracked by 3 wall-mounted cameras employing infra-red technology (ProReflex, Qualisys AB, Sweden). Light-weight (<5 g) infra-red markers were placed on the wrist, thumb- and forefinger-nail of this hand and on the top center of the objects. The 3D spatial coordinates of each marker were recorded at 60 Hz and an accuracy of <0.4mm, between the time of the current signal sent to the liquid-crystal shutters and return of the hand to the start position. Movements were analysed from the resultant 3D motion of the markers on the hand.

2.2.1. Task conditions

The targets on these trials were one of two white or black cylindrical objects of the same height (100 mm) but different widths and weights (23 mm/32 g, 46 mm/128 g). That is, with very similar dimensions to the 'small' and 'large' household items we used in previous studies (e.g., Grant et al., 2007; Melmoth et al., 2009). The objects were positioned at one of two locations; 25 cm from the start button along the subject's midline or at 40 cm and 10 degrees to either the right or left of the start button (depending on the subject's right or left hand dominancy, respectively). Object sizes and distances were also pseudo-randomized across views, with equal numbers of each trial-type per block. There were 4 blocks of experimental trials.

The first 2 blocks contained 24 trials each and were performed under normal lighting (average ~64 cd/m²) using white objects presented against the black background of the table, these representing the standard High Contrast task condition. The other 2 blocks consisted of 36 trials each and were performed under Low Contrast or Low Visibility conditions, the order of which was counter-balanced across the two subject groups. The Low Contrast task used black objects presented on the black background under normal lighting, while the Low Visibility task used the white objects of the High Contrast condition, but with the laboratory black-out curtains closed and the room lights dimmed so that the average luminance (~0.06 cd/m²) was reduced by about 3 log units compared to the standard task. To ensure that participants were affected to a similar degree in the Low Visibility condition, their CS was re-tested with another version of the Pelli-Robson chart in the dim illumination of the laboratory before starting this experimental block. To do this, the lighting was adjusted for each subject, so that the CS of their non-dominant eyes across participants was reduced by a similar degree. Overall, the mean reductions achieved were between 1.22-1.29 log units in each subject group under each of the 3 views, such that the statistically non-significant differences in CS described above were maintained.

2.3. Hand movement indices

Each recorded movement was broken down, using custom-written programs in Matlab software (The Math Works, Cambridge, UK) into 9 kinematic and 3 spatial 'error' indices, allowing various aspects (e.g., planning *versus* guidance; reach *versus* grasp; speed *versus* accuracy) of its performance to be quantified and assessed. These indices are depicted in the different movement 'profiles' shown in Figures 1 & 2, are ones that we have provided rationales for before, and have shown to be affected in adults with a history of amblyopia (e.g., Grant et al., 2007; Melmoth et al., 2009).

In brief, two general kinematic measures were: (1) the movement onset time (between shutter opening and the resultant velocity of the wrist marker first exceeding 50 mm/s) representing the latency period for detecting the target and in planning and initiating the movement towards it; and (2) the movement duration or total execution time (from its onset to the moment that the target was first displaced or lifted by ≥10 mm). Specific kinematic parameters of the reach were: (3) its peak velocity (maximum wrist velocity) and (4) the time to peak velocity after movement onset; and (5) the time spent in the later 'low velocity' or approach phase (between peak wrist deceleration and initial contact with the object). Specific grasp kinematics were: (6) the time to peak grip after movement onset; (7) the grip closure time (from the peak grip to initial object contact); (8) the grip size at initial contact (gap between thumb and forefinger when the target was first displaced by ≥ 1 mm); and (9) the post-contact time (from initial contact to displacing/lifting the target). Indices of the early stages of the reach (peak velocity; time to peak velocity) and of the grasp (time to peak grip) are recognized to be mainly products of movement planning, whereas later stage measures reflect periods in which visual (low velocity reach phase; grip closure time) or non-visual (post-contact time) feedback may be used for on-line control to improve upon or subsequently correct errors in end-point movement accuracy (e.g., the grip size at contact).

To expand upon the latter issue of accuracy, the profiles obtained of each movement depicting the spatial path of the wrist marker (reach) and the aperture between the thumb and finger markers (grasp) were examined for the presence of performance errors. Those related to the reach were; (1) misdirected reaches (see Fig.2B-D), comprising late forward, lateral and/or extra curved ('movement units') course corrections in the wrist spatial path before object contact, these errors being indicative of inaccurate target localization. Those related to the grip profile were: (2) pre-contact and (3) post-contact grip corrections, comprising additional re-opening/closing ('movement units') of the digits either just before or just after (see Fig.1B) initial object contact, these being indicative of 'uncertain' or inaccurate initial formation and application of the grasp, respectively.

[Figures 1 & 2, near here]

2.4. Data analyses

To analyse the data, the median values of each kinematic index and the mean occurrence per trial of each error type in each participant under each view and task condition were calculated, collapsed across object sizes and locations (i.e., trial-types). Values obtained from just the High Contrast task were initially passed through 2 group (control, amblyopia) x 3 views (both, dominant, non-dominant eyes) repeat measures ANOVA (Huynh-Feldt-adjusted, as required), with the Bonferroni test conducted *post hoc* to examine the source(s) of any main effects of view. This was to verify that the patients exhibited the kinds of deficits we have observed before on the standard task. Subsequent planned ANOVA were then conducted, as above, but incorporating the values obtained from the 3 task (High Contrast, Low Contrast, Low Visibility) conditions, as a direct test of our main hypothesis.

Two further analyses were undertaken, just between the amblyopia group members, to assess the possible impact of their different visual losses on their generally poorer performance. First, additional (3 view x 3 task) ANOVA were conducted with different sets of 2 ordinal categories as between-patients factors: (1) their 'cause', defined as strabismus only (n=6) or mixed (n=7); (2) amblyopia severity, defined by their interocular VA differences as being either 'mild' (≤0.40; n=7) or 'moderate' (>0.40; n=6); (3) affected eye CS loss, defined (relative to the lower non-dominant eye limit of the controls) as either 'normal' (n=8) or reduced (n=5); and (4) stereo vision, defined as reduced (n=6) or as nil/unmeasurable (n=7). This approach thus examined the possible involvement of each of the 3 major dimensions of their visual impairment, which Spearman's rank order correlation analyses indicated were independent factors, since these revealed no significant associations between the levels of VA, CS or SA losses among our patient cohort (all P<0.3, $p>0.3$). Second, separate Spearman's correlation analyses were conducted of the possible relationships between the 4 sets of ordinal category in each amblyopia subject with each hand movement index by view and task condition. These analyses employed SPSS software (version 21, IBM Corporation, Armonk, NY, USA). Significance was set at $p<0.05$ for the results of ANOVA, but at a more conservative threshold of $p<0.01$ for the correlation analyses, to minimize the occurrence of Type 1 (false positive) errors.

RESULTS

Average data related to the median hand movement kinematics and mean error-rates/trial in the two subject groups, by view and task condition are presented in Tables 2 & 3, with some selected parameters illustrated in Figures 3-7. We begin by highlighting the main between-group differences in reach-to-precision grasp performance in the High Contrast task only. This is an important preliminary, as it establishes that our current patient cohort exhibited similar deficits to those of other amblyopic adults we have tested previously under this standard condition. We then examine whether the performance deficits in the amblyopia subjects were selectively exacerbated, as we hypothesized, compared to the controls on the Low Contrast and Low Visibility tasks. Finally, we explore any relationships between the nature and severity of the patient's visual disorders and their hand action control.

[Tables 2 & 3, near here]

3.1. Effects of Group and View on the standard High Contrast task

There were several main between-group effects on the standard task, all of which pointed to generally slower and less accurate performance, occurring across each of the 3 views, in the amblyopia subjects. Movement onsets (see Fig.3) were significantly prolonged (by an overall mean of ~90 ms or ~20%) among these participants compared to the control subjects ($F_{(1,24)}$=9.7, p=0.005). This was followed (see Fig.4) by similarly prolonged (by ~140 ms or ~15%) overall movement execution times ($F_{(1,24)}$=8.1, p=0.009). Increases in the times spent in the earliest (planned) components of both the reach (time to peak velocity) and the grasp (time to peak grip), and in applying the grip to the objects right at the end (i.e., the post-contact time) were mainly responsible (all $F_{(1,24)}$>4.7, p<0.040) for the patient's longer movement durations (Table 2). Performance errors in the amblyopia group mainly consisted of increased rates per trial of misdirected reaches (~x4; Figs.2B-D) and of post-contact corrections to the grip position (~x2.25; Fig.1B) across all views (Table 3) compared to the control subjects (both $F_{(1,24)}$≥4.5, p<0.05).

Main effects of view occurred for every performance index, aside from the times to peak velocity and to peak grip. These effects were due to better (i.e., faster, more accurate) performance by both subject groups when using both eyes together compared to either eye alone or just to non-dominant eye viewing. There were no significant group x view interactions for any parameter, but some strong statistical trends consistent with our previous findings. In particular, for the times spent in the low velocity reach phase ($F_{(1,24)}$=2.8, p=0.070) and in grip closure ($F_{(1,24)}$=3.4, p=0.050), there were indications of 'binocular advantages' over monocular viewing among the control subjects, but not the amblyopia group, with these aspects of visual guidance being similar across all 3 views (see Fig.5).

[Figures 3 & 4, near here]

3.2. Effects of Group and Task Conditions

Results of the full 2 x 3 x 3 (group x view x task) ANOVA revealed that the same overall between-group differences occurring on the standard task, also applied when the data from the Low Contrast and Low Visibility conditions were added to the analyses (see Tables 2 & 3). There were also, as expected, main effects of the task conditions on almost every performance measure. As exemplified by movement durations (Fig.4), however, most of these resulted from significantly slower or inaccurate movements *only* in the Low Visibility condition compared to the High and/or Low Contrast object presentations in both subject groups. While they included early (planned) and late (guided) components of both the reach (e.g., reduced peak velocities, increased low velocity phases and spatial path errors) and the grasp (e.g., increased times to peak grip and in grip closure) as we hypothesized, *relative* deficits in the Low Visibility task were no different between control and amblyopia groups. We confirmed this important result by undertaking additional (unplanned) comparisons between just the High Contrast and Low Visibility conditions – that is, with the Low Contrast data excluded from the ANOVA – and still found no significant group x task interactions. Also contrary to our main hypothesis, the 3 parameters that were not affected by the task conditions included defective aspects of reach planning (time to peak velocity) and grip positioning (post-contact times; grip correction rates) on the standard task by the amblyopia subjects that we expected to deteriorate further with the less visible objects. But these parameters were unaffected in the control group too, showing that they were generally immune to the demands of the 'harder' tasks.

Movement onset times and grip sizes at initial object contact did, however, show significant differences (both $F_{(2,48)}>10.0$, $p<0.001$) between the High and Low Contrast conditions. Further analyses revealed that this was because they were the *sole* parameters to demonstrate group x task interactions consistent with exacerbated deficits in the amblyopia subjects. As shown in Figure 3, the interaction for movement onsets ($F_{(2,48)}=3.6$, $p=0.041$) arose because, in the controls, these times were similar regardless of the object's contrast ($p=1.0$) but increased significantly in the Low Visibility condition ($p\leq0.001$ for both comparisons), whereas among the amblyopia group, significant increases occurred between the High Contrast and *both* ($p<0.005$) the Low Contrast and Low Visibility tasks. Similar results (see Fig.6) pertained to the grip size at contact interaction ($F_{(2,48)}=6.7$, $p=0.003$), with significant increases (i.e., reductions in end-point accuracy) occurring between the High and Low Contrast compared to the Low Visibility conditions in the normal subjects (both $p<0.04$), but between the High Contrast and the more demanding Low Contrast and Low Visibility tasks in those with a history of amblyopia (both $p<0.02$).

[Figures 5-7, near here]

3.3. Effects of Group, View and Task Conditions

In addition, the trends towards a selective binocular advantage among the control *versus* amblyopia group for time in the low velocity reach phase and in grip closure on the standard task achieved statistical significance in the full ANOVA with all task conditions considered, as did the rates/trial of pre-contact grip correction (Table 3). As shown in Figure 5, these group x view interactions (all $F_{(2,48)}>4.25$, $p<0.025$) mainly occurred because, unlike the amblyopia subjects with reduced or absent binocularity, these parameters were hardly affected in the controls when they were able to use normal binocular vision for on-line movement guidance in the Low Visibility condition. There were also some hints in the data that the amblyopia subjects performed poorest on some parameters, including movement onsets and durations (Figs.3B & 4B), when using their affected eye in the Low Visibility condition. But there were no significant 3-way interactions between these factors for any parameter.

3.4. Effects of the Vision Losses among Amblyopia group members

Further comparisons revealed no main effects at all with the ordinal categories of ‘cause’ (strabismus *versus* mixed), VA loss (mild *versus* moderate), or stereo vision (reduced *versus* nil) as factors between patient sub-groups. But there were stereo x view interactions for movement durations, misdirected reaches and post-contact times (all $F_{(2,12)} \geq 4.7$, $p<0.033$). These were all due to selectively better (faster, fewer errors) binocular compared to monocular performance in the stereo-reduced sub-group *versus* more equal performance across all 3 views in those who were stereo-nil. Sub-dividing the patients by their affected eye CS (normal *versus* reduced), however, revealed one main effect; on misdirected reach error rates ($F_{(1,11)}=7.6$, $p=0.019$). As shown in Figure 7, this was due to the CS reduced subjects making twice as many (mean = 0.23 ± 0.07 sd) of these errors/trial than those whose CS was within the normal range (mean = 0.11 ± 0.07 sd). Correlation analyses extended this finding. While there were various, isolated small-to-moderate relationships between the ordinal degrees of the patient’s vision losses and various performance indices, the only consistent correlations obtained were between this ordinal measure of CS loss and misdirected reaching with dominant eye and with affected eye viewing on the Low Contrast task (both $P \geq 0.82$, $p \leq 0.001$; Fig.7), with a similar trend for the non-dominant eye in the High Contrast condition as well ($P=0.60$, $p=0.030$). To explore this relationship further, we examined possible linear (Pearson) correlations between the patient’s affected eye (logunit) CS and misreaching rates across views and tasks. As might be expected from Figure 7, this also revealed similarly significant, direct relationships between the two factors for both ($r \geq 0.73$, $p \leq 0.005$) monocular views on the Low Contrast task.

DISCUSSION

Our present findings confirm numerous reports from our own and other laboratories that two eyes are significantly better than one in normally sighted adults for mediating fast and accurate reach-to-precision grasp actions under ‘favourable’ high object contrast task conditions (see Goodale, 2011; Grant & Moseley, 2011), with the nature of the binocular advantages consistent with providing benefits for movement planning and for on-line control. We also confirm evidence of generally poorer performance among adults with amblyopia and/or abnormal binocularity under these same favourable conditions. As previously, we found no clear relationships between the performance deficits and the mainly mild-to-moderate VA losses (e.g., Grant et al., 2007) among the current amblyopia cohort, but with certain aspects of their ‘binocular’ performance, such as increased spatial reaching errors indicative of target mis-localization, worse in those with unmeasurable (nil) compared to reduced stereo vision (e.g., Melmoth et al., 2009). Non-binocularity did not significantly influence performance under either low object visibility condition. But reduced CS (at ~1cpd) was associated with increases in these target mis-localization errors, when using the dominant or affected eye alone on the Low Contrast task.

Finally, in relation to previous findings, we confirmed that requiring adult control subjects to plan and execute their movements under Low Visibility conditions had major, detrimental, effects on their performance. Indeed, the results were similar to those obtained in other experiments (Churchill et al., 2000; Melmoth & Grant, 2012) conducted under very dim lighting, although with the targets and hand parts 'glowing-the-dark'. Movement onsets were delayed, and their durations were prolonged and less accurate than under full lighting, high contrast conditions. Lowering the ambient illumination should have little or no effect on relative contrast between target and background, but does markedly reduce the range of environmental context cues available. As Churchill et al (2000) suggested, this should result in two major 'uncertainties' for the observer. First, in judging the precise distance and direction (i.e., egocentric location) of the goal objects during movement preparation, this information being necessary for efficient planning and directing of the reach. Second, in visually monitoring hand position changes relative to the object and its surroundings for on-line guidance of the reach and grasp. In this context, we would note that while our data suggest that key parameters of on-line guidance, such the final object approach time (Fig.5), were hardly affected when binocular vision was available to the control subjects in the Low Visibility task, this did not prevent a significant loss of end-point grasping accuracy (Fig.6).

Given that our current patient cohort exhibited deficits on the standard high contrast task in preparing their movements (increased onset times), in localizing the targets (increased misdirected reach-rates) and with aspects of on-line grasp control (increased post-contact grip corrections), a major new finding was that they were at no greater disadvantage on the Low Visibility task than the control subjects. That is, while starting from a worse base, their movement onsets and misdirected reach- and late grip correction-rates did not increase *relatively* more than the control group in this condition. The other major new findings were that while there were no differences at all in the performance of the normal adults in the High compared to Low Contrast tasks, low object contrast significantly exacerbated the delay in movement onsets and inaccurate end-point grips of the amblyopia group, and posed a particular difficulty for target localization among the sub-group with reduced CS.

4.1. Deficits in movement planning

Movement onsets were delayed in the amblyopia participants regardless of view – that is, including with their dominant, non-amblyopic eye – and this was most evident when the targets were presented at low contrast relative to the background. The time to hand movement onset is a widely accepted index of the overall planning or reaction period. However, this 'parameter' comprises multiple distinct components; from (i) initially detecting the presence of the target (i.e., at goggle opening); followed by (ii) planning and executing a saccade to fixate it in central vision (e.g., Johansson et al., 2001); so that (iii) its detailed properties (e.g., 3D location, size, shape) can be encoded and provide the evidence necessary to generate an internal model for the up-coming action plan; then (iv) selecting this most appropriate response from amongst a stored repertoire of possible actions (e.g., Rosenbaum et al., 2001); before (v) finally programming and initiating the desired motor output. So problems with which of these might underlie the delayed onsets across all views in our amblyopic subjects and, especially, in the low contrast task?

Experiments conducted by Farzin and Norcia (2011) on adult amblyopes with similar overall characteristics to those of our patient cohort revealed no differences in simple (stimulus detection) or choice (stimulus discrimination) 'button-press' reaction times between affected or dominant eyes or with normal eyes (i.e., in control subjects) nor in reaction times of these subject groups to auditory stimuli. By contrast, reactions when using *either eye* in the amblyopes were significantly delayed, compared to normal eyes, under conditions requiring more complex decision-making in which the response selected was made following the resolution of conflicting visual evidence. Taken altogether, Farzin & Norcia (2011) concluded that it is the intermediate stages (i.e., (iii)-(iv), above) of visual evidence evaluation and response selection that are defective in both eyes in amblyopia, and that this may result from binocular dysfunctions in the inputs to and/or within parieto-frontal cortical regions.

Since all of our amblyopia participants had some degree of binocular dysfunction in common, we suggest that a similar problem, in which extra time was required to accumulate ('uncertain') visual evidence about the 3D target properties may account for their generally delayed movement onsets. In the case of the Low Contrast condition, this general problem may have been compounded by the presence of 'global' signal-from-noise processing deficits affecting their ability to segregate the black targets from the black background. Deficits in saccade planning among adult amblyopes of different sub-types offer support for these suggestions. Specifically, Niechwiej-Szwedo et al (2010, 2011b, 2014) have found that, whereas primary saccade latencies (reaction times), are selectively delayed *only* in the affected eye of moderately-to-severely amblyopic subjects – that is, a likely stimulus-detection deficit – the planning interval between initial target fixation and start of the reaching hand movement (i.e., also stages (iii)-(iv), above) are often significantly extended across 'binocular', dominant eye and affected eye views compared to controls. Moreover, like saccade performance in general, such post-initial fixation delays tend to be worse among amblyopia subjects who are also non-binocular (i.e., stereo nil).

4.2. Compensatory motor control strategies

That these implied 'uncertainties' in evaluating the target's 3D location and size/shape during movement preparation remained less well resolved in our amblyopia compared to control participants, however, is strongly suggested by the fact that they significantly prolonged the initial phases of both their reach (time to peak velocity) and their grasp (to time peak grip), effects which also occurred across all 3 views and task conditions. We have not previously compared times to peak velocity (i.e., the duration of the acceleration phase) between these adult subject groups, but were motivated to do so here by previous results of pointing experiments. In particular, Niechwiej-Szwedo and colleagues (2011a, 2011b, 2012a, 2102b, 2014) have consistently shown increased acceleration phases across all views in strabismic and non-strabismic adults with or without persistent amblyopia when pointing to targets, whether presented on a computer monitor or in more real-world 3D space. Their evidence also suggests that this slower time to peak velocity results from uncertainties about target location and, interestingly, that it represents a 'compensatory' motor control strategy associated with enhancing end-pointing precision, whereas control subjects achieve this latter by using visual feedback later in the reach, by prolonging its low velocity (or deceleration) phase. Our new data would, therefore, suggest that a similar adaptive strategy was employed by our current patient cohort in an attempt to, at least partially, compensate for anticipated inaccuracies in their subsequent reaching performance. Similar arguments would apply to the increased times to peak grip (Table 2), which we have observed before (e.g., Grant et al., 2007; Melmoth et al., 2009), in relation to the final grasp accuracy. That the compensations were only partial is signalled by the fact that their spatial reach path- and post-contact grip correction-rates remained significantly greater across all views and tasks than those of the normally sighted subjects.

These adaptations would be in addition to another apparent motor control strategy of extending their time contacting and manipulating the objects before picking them up. This, too, was a major between group-difference that occurred across all views and tasks, and is one that we have consistently seen before under high contrast conditions in children and adults with amblyopia and/or abnormal binocularity (Grant et al., 2007, 2014; Melmoth et al., 2009; Suttle et al., 2011). While the increased rates of post-contact grip correction would have contributed to the longer manipulation times in these subjects, such errors occur on relatively few (i.e., only ~10-15%) of all trials (Table 3). Instead, prolonged post-contacts are more commonly associated with long plateaus at the very end of the grip profile in which the thumb and finger positions do not change at all for periods that can last several 100 milliseconds. We have interpreted these as an attempt to gain extra tactile and/or kinaesthetic feedback from the digits regarding the stability of the initial grip. This would be to partially compensate for temporal processing deficits in people with binocular dysfunctions that make it as difficult as for them as for control subjects using monocular vision (see Greenwald et al., 2005) to acquire fast and reliable visual feedback for digit guidance during the short 'in-flight' period of the movements in which the hand is finally approaching the target (e.g., Fig.5).

4.3. End-point grip precision

Overall, the patient group showed other uncertainties in grasping compared to the controls, including making more pre-contact corrections to their digit positions when closing their grip on the objects with both eyes open. But the only grasp index selectively affected by the task conditions was an increase in the grip size at initial contact with the low contrast objects. This may have occurred for a similar combination of reasons to those discussed above, whereby the patients had particular difficulty visually identifying the best opposing contact points on the black objects before beginning their movements. But another notable feature of their performance was that, after spending so long initially reacting to these particular objects (Fig.3B), the amblyopia subjects spent a relatively short time executing their movements towards them, especially in the low velocity reach (Fig.5B) and grip closure phases (Table 2). In other words, their movements appeared somewhat 'ballistic' in the Low Contrast task, as if they had dispensed with any serious attempt to use visual feedback for on-line guidance during the final object approach, a factor that could have contributed to their reduced precision when grasping the black targets.

4.4 Potential limitations and conclusion

A potential limitation in our experimental protocol may also have contributed to this somewhat ballistic tendency, in that the Low Contrast trial-block was always administered after extended performance on the High Contrast task. This procedural feature was, however, specifically designed to reduce the impact of a potentially much greater problem that might have occurred had we counter-balanced these block presentation sequences. This problem relates to our previous observation that, even after providing pre-test practice, some aspects of performance can be particularly poor on the first set of proper experimental trials among subjects with abnormal binocularity, but not with normal vision (Grant & Moseley, 2011). That is, we wanted to ensure the amblyopia subjects had stabilized their performance on the standard task, so that any evidence obtained for additional deficits in the later, more challenging low object visibility conditions could not be attributed simply to their unfamiliarity with the general task procedures.

Amblyopia is notoriously heterogeneous in its origins, visual consequences and responses to treatment. Our limited sample of 13 participants with a history of the disorder reflects this. Indeed, two of them (S1, M1) were no longer amblyopic according to the conventional criterion of a 2-line interocular VA difference. This prompted an Anonymous Reviewer to question our decision to include these two subjects in the analyses and to ask if it had a major impact on the results. We originally included them because according to an alternative and, possibly, more functionally meaningful criterion of non-binocularity (McKee et al., 2003), they could be viewed as being severely affected by their developmental history. Nonetheless, at the Reviewer's behest, we re-analyzed all the data with these 2 patients excluded, along with their matched controls. The sole impact was to eliminate the stereo x view interactions (see section 3.4) initially found between the small sub-group of stereo-reduced *versus* (now smaller) sub-group of stereo nil participants. Crucially, though, the exclusions made no difference to our main findings regarding the lack of a between-group deterioration in *relative* performance on the Low Visibility task; nor on the selective accentuation of the general deficits in movement onsets or grip sizes at contact with the low contrast objects (both group x task interactions now $F_{(2,40)} \geq 6.0$, $p \leq 0.005$); nor on the correlations between reduced CS and additional mis-reaching errors on this specific task (as per section 3.4; Fig.7).

We had anticipated that the non-binocular and/or reduced CS patient sub-groups might show the worst performance on both of the more difficult tasks. But these latter relationships were the only evidence obtained in accord with this conjecture. The sub-group sample sizes were small and we only screened contrast sensitivities at one, very low, spatial frequency, and so have no information about their potential CS losses at higher spatial scales. It is, therefore possible, that other subtle relationships with degree of vision loss may have been revealed by increasing the number of amblyopic participants studied and the screening range. We considered this unwarranted, however, because the deficits exhibited by individual patients – including case M7 who had the most seriously reduced vision across all three major dimensions (Table 1) – relative to the mean performance of the control subjects (e.g., beyond their upper bound 95% confidence limits) on the lower visibility tasks were not obviously greater than others, such as M2, who had very mild amblyopia, 'normal' CS and only slightly reduced stereovision.

For all of the above reasons, we can thus be confident in our current findings. Indeed, it would now appear that loss of binocularity needs to be accompanied by severe reductions in CS – and, possibly, in VA – in *each eye*, such as can occur in patients with binocular macular disease, before more notably impairing multiple parameters of reach-to-precision grasp execution under low object visibility conditions (Pardhan et al., 2012). In sum, we conclude that adults with a history of amblyopia and binocular dysfunction show little additional impairment, over and above their poorer baseline deficits, on reach-to-precision grasp tasks that pose real challenges for patients with severe visual impairment in both eyes.

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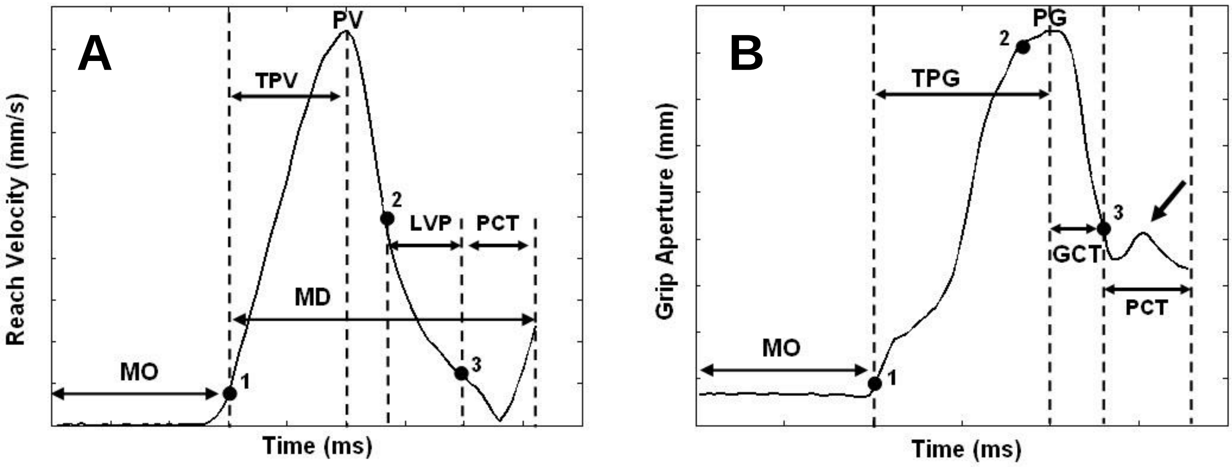

Figure 1: Reach velocity (A) and grip aperture (B) profiles, showing key landmarks in the movements from which the 9 kinematic parameters were derived. The cue to move (i.e., goggle lens opening) occurred at time zero on the x-axis. Movement onset (MO) began when the wrist marker first exceeded a resultant velocity of 50 mm/s (*filled circles*, labelled 1). The moments of peak deceleration (PD) of the wrist (*filled circles*, labelled 2) and of initial object contact (OC), when then the marker on the targets was first displaced by ≥1mm (*filled circles*, labelled 3) are shown in both profiles, with the *dotted lines* and *double-headed arrows* between them indicating: in (A) the total movement duration (MD) between MO and the end of the movement when the marker on the target was first displaced by ≥10mm; the time to peak velocity (TPV) of the reach, its peak velocity (PV) and low velocity phase (LVP) between PD and OC; and the post-contact time (PCT) after OC (during which the increase in wrist velocity was due to the target being lifted); and in (B) the time to peak grip (TPG) aperture between the thumb and finger markers and the grip closure time (GCT) between this and OC; with the grip size at contact derived from the aperture (on the y-axis) at the moment of OC in the profile. Note the late re-opening and closing of the grip aperture ('movement unit') that occurred during the PCT in this profile (*arrowed*), which is a representative example of the 'post-contact grip correction' error measure.

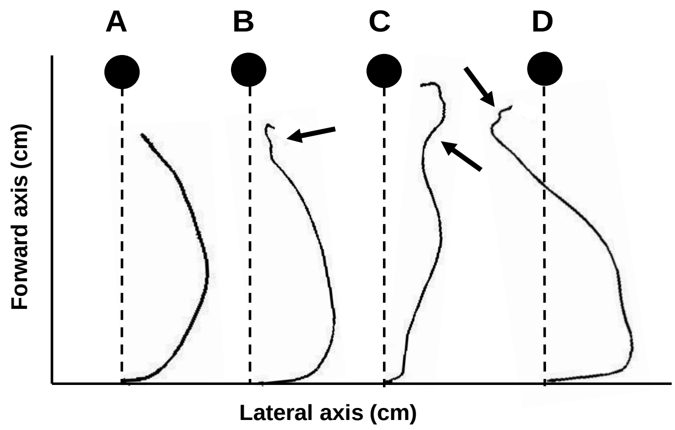

Figure 2: Spatial path profiles showing (A) a normal reach and (B-D) representative examples of misdirected reaches by right-handed subjects towards the larger targets (*filled circles*) at the near, midline location. The reach paths (*solid traces*) have been collapsed into their forward (y-axis) and lateral (x-axis) components, with the *dotted lines* indicating the shortest Euclidean distance between the start point of the wrist and the center of the targets. In (A) the reach path follows a typical curved trajectory, moving in a rightward direction on the lateral axis, and terminating just short of the target (as it was measured from the marker on the wrist), but the misdirected reaches involve late corrections (*arrows*) to their initially curved trajectories, occurring as (B) forward, (C) extra curved, and (D) lateral changes in the spatial path prior to object contact.

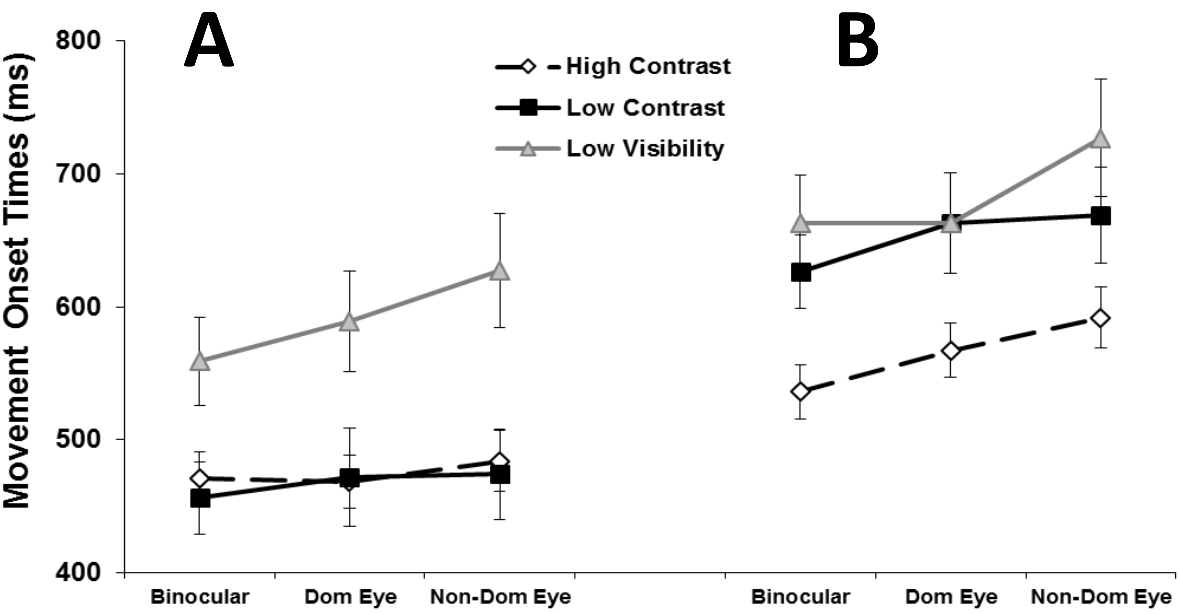

Figure 3: Average movement onset times in (A) control and (B) amblyopia subjects by view and task conditions. Dom, dominant eye; Non-Dom (non-sighting eye in controls; affected eye in amblyopia subjects). Errors bars, SEMs.

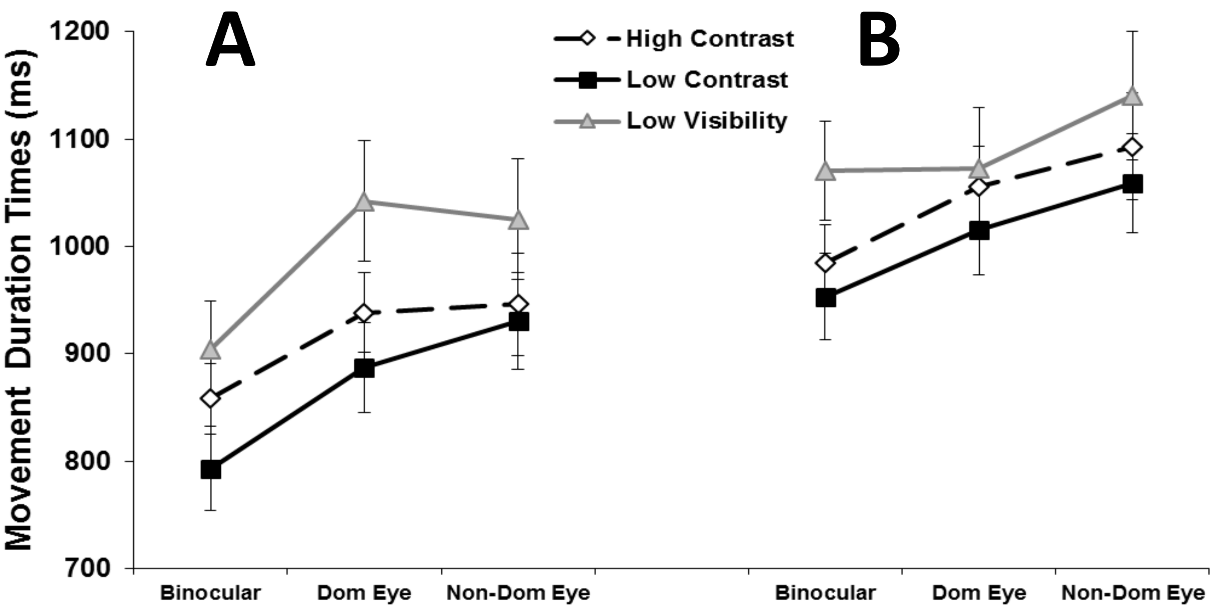

Figure 4: Average movement duration times in (A) control and (B) amblyopia subjects by view and task conditions. Conventions, as in Figure 3.

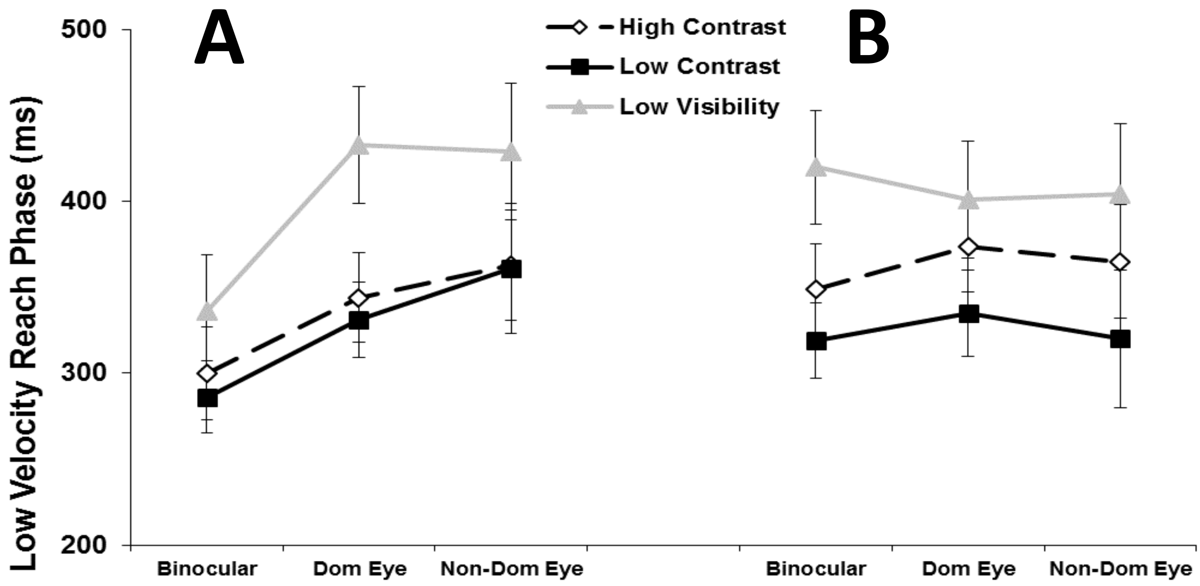

Figure 5: Average times spent in the low velocity phase of the reach in (A) control and (B) amblyopia subjects by view and task conditions. Conventions, as in Figure 3.

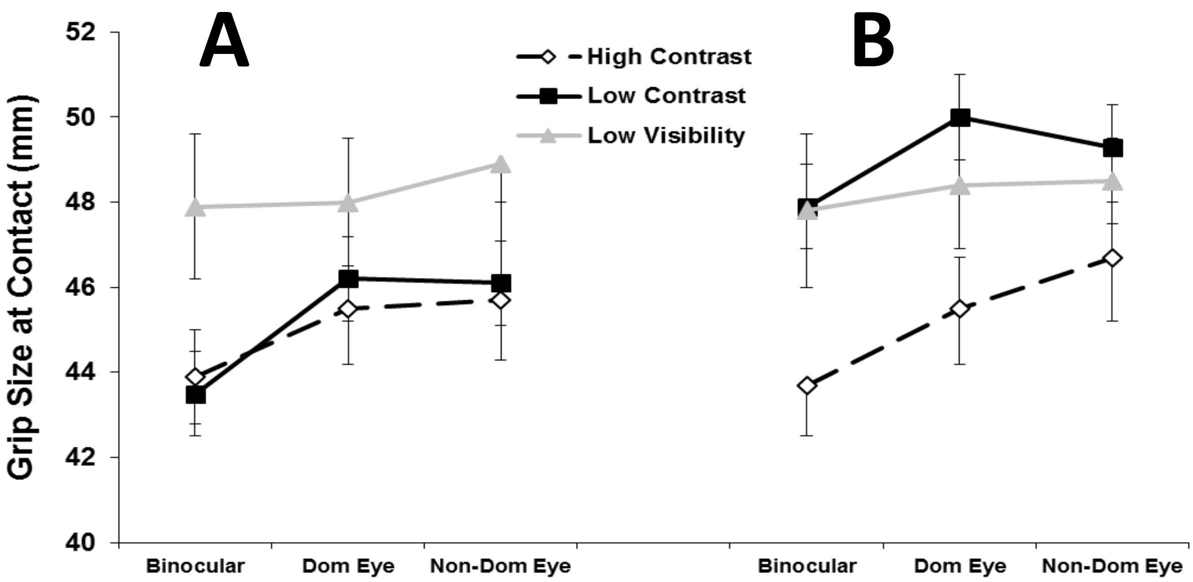

Figure 6: Average grip sizes between thumb and finger at initial object contact in (A) control and (B) amblyopia subjects by view and task conditions. Conventions, as in Figure 3.

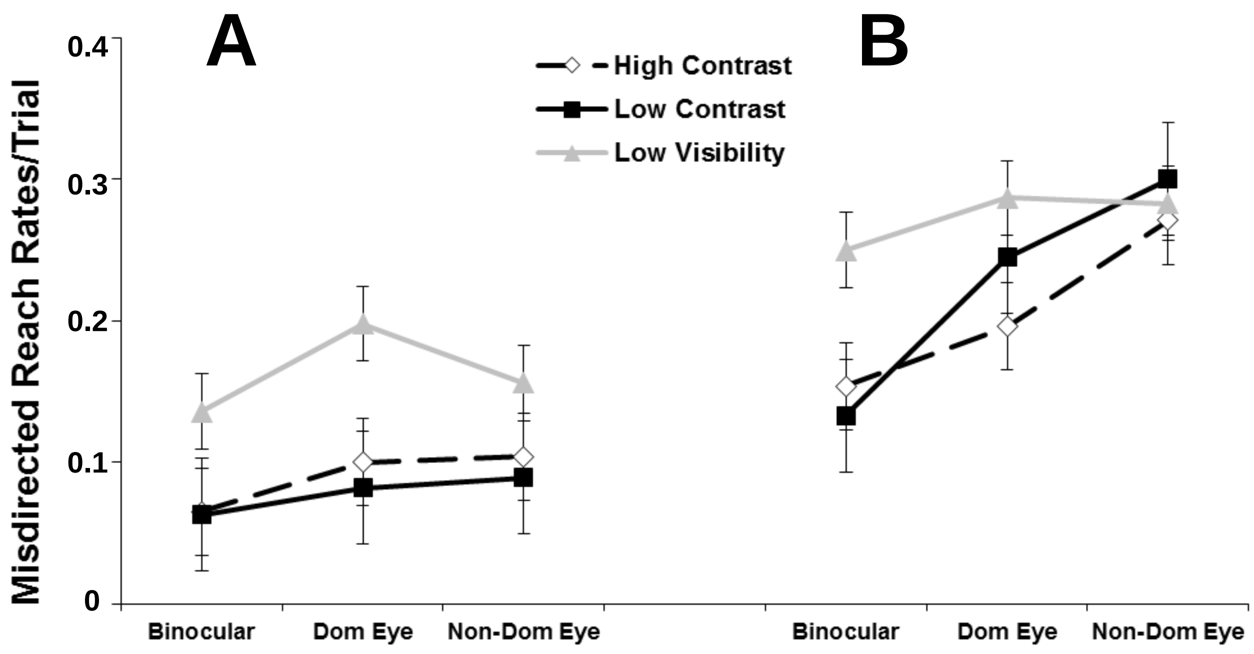

Figure 7: Average misdirected reach error rates per trial in the sub-groups of amblyopia subjects with (A) 'normal' and (B) reduced contrast sensitivity by view and task conditions. Error bars, SEMs.

TABLE 1. Details of the Amblyopic Subjects

Type	Sex, Age	Refraction	Visual Acuity (logMAR) BO	DOM	N-D	iod	Contrast Sensitvity (log) BO	Dom	N-D	iod	Stereo arc secs	Observations
S1	M, 43	L +10.50/-2.00@100 R +10.50/-2.75@45	0.00	0.00	0.02	0.02	1.65	1.65	1.55	0.10	Nil	Amblyopia detected age 3 y, patched 3-5 y, surgery 6 y, now L XT 40Δ
S2	M, 21	L +1.75/-1.25@180 R +1.75/-1.25@180	0.02	0.02	0.32	0.30	1.80	1.70	1.65	0.05	200"	Amblyopia detected age 1 y; patched 3-5 y, now micro R ET 4-6Δ
S3	F, 21	L -1.25/-0.50@75 R -0.50/-0.25@75	0.06	0.10	0.44	0.34	1.65	1.55	1.45	0.10	400"	Amblyopia detected age 4 y, patched 4-5 y now micro R ET 4-6Δ
S4	F, 20	L -5.00/-1.25@110 R -5.00/-0.75@20	0.02	0.02	0.50	0.48	1.60	1.60	1.40	0.20	400"	Amblyopia detected age 4 y, patched 5-6 y now micro R ET 4-6Δ
S5	F, 41	L +3.00/-0.50@30 R +3.00/-0.25@40	0.00	0.00	0.74	0.74	1.90	1.85	1.65	0.20	Nil	Amblyopia detected age 8 y, patched 8-10 y nowL ET 30Δ
S6	M, 41	L +1.00 DS R +1.25/+0.25@135	-0.08	-0.08	0.80	0.88	1.90	1.90	1.65	0.25	Nil	Amblyopia detected age 3 y, patched 3-5 y, surgery 7, 11 & 18 y, now R ET 30Δ
M1	M, 33	L +4.00 DS R + 6.50 DS	-0.04	-0.02	0.06	0.10	1.65	1.65	1.60	0.05	Nil	Amblyopia detected age 3 y, patched 3-5 y, now R ET 35-45Δ
M2	F, 19	L plano R +3.25 DS	-0.08	-0.08	0.12	0.20	1.90	1.90	1.65	0.25	400"	Amblyopia detected age 2 y, surgery 3 y, patched 5-6 y, now R ET 10Δ
M3	F, 19	L -4.75/-1.25@70 R -0.50/-0.25@120	-0.08	-0.08	0.32	0.40	1.80	1.65	1.30	0.25	100"	Traumatic cataract 5 y, no treatment, now L micro XT 6Δ,
M4	F, 30	L +3.50 DS R + 5.25 DS	-0.06	-0.02	0.40	0.42	1.90	1.85	1.80	0.05	Nil*	Amblyopia detected age 1 y; patched 3-5 y & 7-9 y, now R ET 20Δ; seen 3D movies*
M5	F, 26	L -2.75/-1.75@30 R plano/-1.75@150	-0.14	-0.14	0.30	0.44	1.80	1.80	1.80	0.00	Nil	Amblyopia detected age 4 y, patched 5-7 y surgeries 7y & 12 y, now L ET 40Δ
M6	F, 18	L +4.25/-0.25@20 R plano	-0.20	-0.14	0.54	0.68	1.65	1.65	1.65	0.00	140"	Amblyopia detected at 7 y, patched 7-10 y now L micro XT 4-6Δ
M7	F, 20	L -3.75/-1.25@170 R -12.50/-0.50@200	-0.12	-0.12	1.00	1.12	1.90	1.90	1.40	0.50	Nil	Amblyopia detected age 3 y, patched 3-4 y now R ET 16Δ

Key: S, Strabismus; M, Mixed, strabismus + anisometropia; S, strabismus; BO, binocular; DOM, dominant (fellow/fixing) eye; N-D, non-dominant (affected, amblyopic) eye; iod, interocular difference (N-D minus DOM eyes); Stereo, best crossed stereoacuity thresshold achieved. ET, Esotropia; XT, Exotropia

Table 2. Mean (± sem) hand movement kinematics by viewing condition and subject group

Dependent Measures	Conditions	Control			Amblyopia		
		Binocular	Dom Eye	ND Eye	Binocular	Dom Eye	ND Eye
Movement Onset (ms)***	Control	471 (18)	468 (17)	484 (18)	536 (20)	567 (21)	592 (24)
	Low Contrast	458 (19)	472 (22)	474 (24)	627 (27)	662 (39)	669 (35)
	Low Visibility	559 (27)	589 (39)	627 (35)	663 (35)	664 (38)	727 (44)
Movement Duration (ms)*	Control	833 (21)	930 (30)	953 (33)	985 (42)	1055 (40)	1094 (52)
	Low Contrast	793 (38)	887 (43)	922 (34)	953 (41)	1015 (40)	1060 (51)
	Low Visibility	889 (42)	996 (47)	994 (45)	1070 (42)	1073 (40)	1147 (51)
Peak Velocity (mm/s)	Control	754 (27)	735 (31)	708 (26)	715 (43)	712 (34)	688 (41)
	Low Contrast	778 (25)	786 (31)	730 (22)	738 (39)	732 (42)	728 (42)
	Low Visibility	737 (25)	697 (34)	673 (21)	720 (40)	704 (39)	688 (49)
Time to Peak Velocity (ms)**	Control	281 (7)	275 (31)	278 (11)	322 (14)	324 (12)	331 (14)
	Low Contrast	274 (8)	271 (9)	281 (10)	324 (19)	323 (19)	310 (12)
	Low Visibility	275 (13)	271 (14)	274 (13)	317 (19)	322 (19)	329 (14)
Low Velocity Phase (ms)###	Control	292 (11)	348 (18)	363 (21)	349 (35)	374 (32)	365 (40)
	Low Contrast	289 (17)	337 (21)	365 (24)	319 (25)	335 (22)	320 (48)
	Low Visibility	344 (21)	457 (39)	429 (41)	420 (36)	392 (27)	404 (41)
Time to Peak Grip (ms)*	Control	489 (14)	497 (19)	509 (23)	554 (26)	567 (24)	566 (26)
	Low Contrast	477 (15)	489 (16)	501 (22)	568 (36)	569 (36)	572 (36)
	Low Visibility	516 (21)	542 (27)	531 (29)	573 (30)	592 (35)	623 (44)
Grip Closure Time (ms)#	Control	223 (15)	274 (15)	293 (15)	277 (27)	289 (28)	292 (26)
	Low Contrast	214 (13)	263 (14)	294 (17)	231 (16)	253 (11)	253 (20)
	Low Visibility	263 (29)	346 (34)	338 (29)	305 (22)	308 (21)	304 (33)
Grip Size at Contact (mm)	Control	43.9 (1)	45.7 (2)	45.7 (1)	43.7 (1)	45.5 (1)	46.7 (2)
	Low Contrast	43.5 (1)	46.2 (1)	44.1 (1)	47.9 (2)	50.0 (1)	49.3 (1)
	Low Visibility	47.5 (2)	48.0 (2)	48.9 (1)	47.8 (2)	48.4 (2)	48.5 (1)
Post-Contact Time (ms)*	Control	126 (9)	151 (11)	146 (12)	156 (9)	175 (11)	205 (13)
	Low Contrast	120 (13)	155 (14)	135 (14)	145 (13)	165 (14)	170 (15)
	Low Visibility	135 (12)	160 (12)	155 (12)	158 (13)	173 (12)	178 (12)

Key: Dom, Dominant; ND, Non-Dominant. Between-Group differences across all Views and Tasks; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$. Group x View interactions; $^{\#}$, $p<0.05$; $^{\#\#\#}$ $p<0.001$.

Table 3. Mean (± sem) reach and grasp error-rates/trial by viewing condition and subject group

Dependent Measures	Conditions	Control			Amblyopia		
		Binocular	Dom Eye	ND Eye	Binocular	Dom Eye	ND Eye
Misdirected Reaches**	Control	0.01 (0.03)	0.04 (0.02)	0.05 (0.03)	0.10 (0.03)	0.15 (0.03)	0.17 (0.03)
	Low Contrast	0.00 (0.03)	0.06 (0.03)	0.05 (0.03)	0.09 (0.03)	0.14 (0.03)	0.17 (0.03)
	Low Visibility	0.03 (0.04)	0.06 (0.04)	0.07 (0.04)	0.20 (0.04)	0.24 (0.04)	0.23 (0.04)
Pre-Contact Grip Corrections[#]	Control	0.01 (0.02)	0.08 (0.03)	0.07 (0.02)	0.05 (0.02)	0.07 (0.03)	0.07 (0.02)
	Low Contrast	0.01 (0.01)	0.03 (0.02)	0.05 (0.02)	0.03 (0.01)	0.05 (0.02)	0.06 (0.02)
	Low Visibility	0.04 (0.02)	0.08 (0.03)	0.05 (0.02)	0.09 (0.02)	0.05 (0.03)	0.05 (0.02)
Post-Contact Grip Corrections**	Control	0.02 (0.01)	0.06 (0.02)	0.07 (0.03)	0.07 (0.02)	0.10 (0.02)	0.17 (0.03)
	Low Contrast	0.03 (0.02)	0.04 (0.02)	0.06 (0.03)	0.08 (0.02)	0.10 (0.02)	0.17 (0.03)
	Low Visibility	0.03 (0.02)	0.08 (0.03)	0.10 (0.03)	0.12 (0.02)	0.15 (0.03)	0.17 (0.03)

Key: Dom, Dominant; ND, Non-Dominant. Between-Group differences across all Views and Tasks; **, p<0.01; Group x View interactions; [#], p<0.05.