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Prehension of a flanked target in individuals with amblyopia

John G. Buckley[1], Ian E. Pacey[2], Gurvinder K. Panesar[2], Andrew Scally[3], Brendan T. Barrett[2]*

1. Division of Medical Engineering, School of Engineering, University of Bradford, Richmond Road, Bradford BD7 1DP, United Kingdom.

2. School of Optometry & Vision Science, Faculty of Life Sciences, University of Bradford, Richmond Road, Bradford BD7 1DP, United Kingdom.

3. Faculty of Health Studies, University of Bradford, Richmond Road, Bradford BD7 1DP, United Kingdom.

*Corresponding author

Abstract:

Purpose: Reduced binocularity is a prominent feature of amblyopia and binocular cues are thought to be important for prehension. We examine prehension in individuals with amblyopia when the target-object was flanked, thus mimicking everyday prehension. Methods: amblyopes (n=20, 36.4±11.7 years; 6 anisometropic, 3 strabismic, 11 mixed) and visually-normal controls (n=20, 27.5±6.3 years) reached forward, grasped and lifted a cylindrical target-object that was flanked with objects on either (lateral) side of the target, or in front and behind it in depth. Only 6 amblyopes (30%) had measurable stereoacuity. Trials were completed in binocular and monocular viewing, using the better eye in amblyopic participants. Results: Compared to visual normals, amblyopes displayed a longer overall movement time ($p=0.031$), lower average reach velocity ($p=0.021$), smaller maximum aperture ($p=0.007$) and longer durations between object contact and lift ($p=0.003$). Differences between groups were more apparent when the flankers were in front and behind, compared to either side, as evidenced by significant group-by-flanker configuration interactions for reach duration ($p<0.001$), size and timing of maximum aperture ($p\leq0.009$), end-of-reach to object-contact ($p<0.001$), and between object contact and lift ($p=0.044$), suggesting that deficits are greatest when binocular cues are richest. Both groups demonstrated a significant binocular advantage, in that in both groups performance was worse for monocular compared to binocular viewing, but interestingly, amblyopic deficits in binocular viewing largely persisted during monocular viewing with the better eye. Conclusions: These results suggest that amblyopes either display considerable residual binocularity or that they have adapted to make good use of their abnormal binocularity.

Introduction

Amblyopia is a moderately prevalent (1.8%-3.6%)[1-3] developmental disorder of vision in which there is a unilateral (or infrequently, a bilateral) reduction in best corrected visual acuity, as well as reduced binocularity[4-6]. Aside from the clinical conditions with which it typically co-exists (anisometropia and/or strabismus), there is no overt structural abnormality or pathology of the eye(s) or the visual pathway, and both eyes are therefore apparently healthy[7].

The study of amblyopia has a long history and there is a vast literature on its associated visual characteristsics[8-11], on its underlying neural basis[12-14] and on its treatment[15-23]. Until relatively recently, however, little was known about the functional consequences of living with amblyopia[24], or with the diminished binocularity that always accompanies it. It is now clear, however, that there are marked differences in visuomotor performance and behaviour between humans with and without amblyopia[25-38], and in individuals with other naturally-occurring binocular vision losses[32,39]. Visuomotor deficits are apparent in a whole variety of real-world tasks, including tasks conducted with the hand (e.g. fine motor control tasks[26,27,31], reach-to-touch movements[32-35], learning to catch a ball [37]) and during whole body movement, for example during gait and obstacle avoidance[36] (for a recent review see Grant & Moseley[40]).

One of the functional tasks that has been most studied in individuals with amblyopia, and with other conditions that characteristically exhibit reduced binocularity, is prehension, or using the hands and fingers to grasp, or pinch or pick up an object. Prehension consists of a reach-phase and a grasp-phase. It represents a fundamental task in human behaviour and it relies on the processing of complex visuo-spatial and proprioceptive information[41]. For efficient performance, the observer must have accurate knowledge about the location of the object within its surroundings and about his/her position relative to the target, and to non-target objects. Proficient reaching involves the transportation of the hand quickly and accurately, initially accelerating and then decelerating as it is moved towards the target, avoiding non-target objects on its way, while proficient grasping requires the hand to open in anticipation of intercepting it. The task of prehension is completed through rapid closure of the hand on parts of the object that are deemed to be stable.

Grant and colleagues[25] compared reaching and grasping behaviour in adults with and without amblyopia. In binocular viewing, initial reaching behaviour and grip shaping prior to contact with the object were relatively unaffected in amblyopes, however a range of deficits was exhibited in the final approach to the object, and in the closure of the hand to apply the grasp. These deficits included prolonged execution times and an increased number of errors during the terminal reach and grasp. Consistent with these findings, Suttle and colleagues[30] found that children with amblyopia took almost twice as long in the final approach to the object and that they made 1.5 to 3 times as many errors than their visually-normal counterparts in reach direction and grip positioning. Melmoth and colleagues[40] studied adults with strabismus but without amblyopia and the pattern of results they obtained was very similar to the results in amblyopes suggesting that prehension deficits in amblyopia have their origins in reduced binocularity, rather than in the visual acuity loss that is characteristic of the condition, a view that has received further recent support[29,38].

The reduced proficiency with which individuals with diminished or absent binocularity, with or without amblyopia, complete prehension tasks is consistent with a view that binocular cues are of particular importance in planning and executing prehension tasks[42-44]. During binocular vision, retinal image disparity cues as well as cues from vergence are available. Initially it was thought that binocular cues may be particularly important for estimating the distance of the target[45] but more recent evidence suggests that the advantage conferred by binocular vision concerns the provision of online information regarding the position of the (moving) hand relative to the target [46-48]. Several studies indicate that the absence or temporary degradation of binocular vision primarily affects the grasp rather than the reach in prehensile movements[25,29,30,38,39,46,49,50]. Despite the large volume of research showing prehension deficits in naturally-occurring binocular vision anomalies[25,29,30,38-40], there is an extant view that the role of binocular vision in the planning and execution of prehensile movements may have been overstated[50-52]. For example, it is clear that binocular vision cannot be essential for prehension: when one eye is covered prehensile movements can still be largely accurate and reliable, e.g. [50,51,53]. At the same time, there is growing evidence that the role of binocular vision is to provide additional cues for the visual system to use and that the weighting of these cues depends on the particular circumstances and target configuration when reaching to grasp[47,51,54,55][also, see discussion]. Thus, from this standpoint, binocular vision plays an important, but not a crucial role in prehension.

The research described here is concerned with an examination of the extent to which everyday prehension performance may be affected in individuals with amblyopia. Two issues are specifically addressed. Firstly, while previous prehension studies in amblyopes, and those with reduced binocularity but without amblyopia, have involved reaching for an unflanked (i.e. lone) target[25,29,30,38,39], we employed a stimulus configuration in which the target to be reached for, grasped and then lifted was flanked, either in front and behind, or on either side. We chose a flanked configuration because targets in the real world are commonly flanked but prehension for non-isolated targets has not been studied in naturally-occurring binocular disorders[38]. Prehension of non-isolated targets has been comprehensively studied in visual normals (e.g. [52,53]). Tresilian[56] showed that visually normals adopt an obstacle avoidance strategy which consists of two related elements; the first involves moving around the non-target object so as not to come too close to it [57], and the second involves slowing down. This means that the presence of an obstacle can affect the transport component, the grasp formation component, or both. Changes to the transport component may also involve a reduction in the movement speed with the result that more time is available for using visual feedback to correct/control the movement path[56]. Changes to the grasp, typically consist of a reduction in the size of the grasp and a change in the timing of when maximum grasp aperture arises so that it arises at a location that will reduce the chances of colliding with the non-target objects. We examined if similar adaptations take place in amblyopes. Also, we wished to determine whether deficits in prehension differed if the target was flanked in-depth compared to when laterally flanked. Given the well-established binocularity deficits that exist in individuals with amblyopia[7,8,10,11] we hypothesised that deficits may be greater for the separated-in-depth condition where binocular cues are richer and thus more central to the task, and that this may have a bearing on the general question concerning the relative importance of binocular vision for prehension.

The other issue we addressed concerns the impact of closing the weaker eye in adult amblyopes. Previous research has shown that there is a binocular advantage in amblyopes but the advantage is smaller than that in visual normals[25]. Other research has shown that the effects of closing one eye in visual normals and the weaker eye in children with amblyopia were similar (though see [29, 30]). A broadly similar pattern of results was recently obtained by Grant and Conway[38]. In the present study, we hypothesised that because amblyopes have reduced binocularity, abolishing binocularity altogether would have a relatively smaller effect than in visual normals.

Methods

Participants

A total of 40 participants took part in the study. Twenty participants were visually normal (mean age 27.5±6.3 years) and they comprised the control group against which twenty amblyopic individuals (mean age 36.4±11.7 years) were compared. Participants were recruited from the staff and student population at the University of Bradford and from the surrounding area. Informed written consent was obtained from all participants prior to their participation, and the tenets of the Declaration of Helsinki were observed throughout.

[Insert Table 1 about here]

Exclusion criteria for the visually normal group included a history of ocular pathology (including strabismus) or amblyopia, or treatment for strabismus or amblyopia. When wearing their habitual correction, visually normal participants had monocular visual acuities (VA) of at least Snellen 6/6 (0.0 logMAR) in each eye and stereopsis of 60 seconds of arc or better on the Frisby stereoacuity test (https://eshop.haagstreituk.com/products/orthoptic-equipment/stereotests). Amblyopic individuals were included if they had an absence of ocular pathology (aside from strabismus), and an acuity difference between the right and left eyes of ≥2 lines [0.20 logMAR].

All participants underwent subjective refraction and binocular vision assessment (Table 1). Ocular dominance was determined in visual normals. We recognise that tests of eye dominance in visual normals may give results that depend upon the test or the protocol. We could simply have chosen the right or left eye at random for monocular viewing in visual normals but we chose the eye to be used for monocular viewing using the Kay pictures dominance test (www.kaypictures.co.uk/dominant.html) on the basis of the eye that was used for sighting on two or more of the three presentations.

In the amblyopic participants, the mean best-corrected visual acuity for the better eye was -0.04 logMAR and the mean acuity for the weaker eye was +0.59 logMAR. In the visual normals, the mean acuity for both the 'dominant' and 'non-dominant' eyes was -0.05 logMAR (Table 1). The mean stereoacuity for the visually normal group was 31.1 seconds of arc whereas in the amblyopes with measurable stereoacuity, stereoacuity ranged from 60 to >600 seconds of arc; fourteen of the twenty amblyopes had no measurable stereoacuity (Table 1). Six of the 20 amblyopes had anisometropic amblyopia (i.e. no strabismus and at least 1.5 D difference in the mean spherical-equivalent refractive error between the eyes). Three had strabismic amblyopia and eleven had mixed (anisometropic and strabismic) amblyopia (Table 1).

Protocol

Participants completed prehension tasks in which they reached forward and picked up a target object (two different diameters) that was flanked by two distractor objects ('flankers'; two different diameters) placed either in front and behind the target object, or on either side of it, and with two different spacings (equivalent to the width of two or four fingers for each individual participant)(Figure 1). Had a fixed separation between target and flankers been used, we believe the task would have been more challenging for participants with larger hands/wider fingers. For this reason we scaled the spacing between target and flankers to take account of differences in hand/finger size.

Participants sat on a stool located directly in front of a table. The height of the stool was adjusted so that the participants sat in a comfortable, upright position with the elbows level with the table top. The table was covered with white cloth (Figure 1). Participants were asked to reach across the table with the arm which they normally use when picking up objects. The object to be grasped was placed at a distance equivalent to 66% of participant's full reach distance.

Participants completed repeated trials in binocular- and monocular- viewing. In monocular viewing, the amblyopes always viewed with their better eye, and the visual normals always viewed with the 'dominant' eye. Viewing conditions were manipulated with the use of Plato liquid crystal display (LCD) goggles (Translucent Technologies, Toronto, ON, Canada).

Participants initiated movement when either both lenses or one lens of the LCD goggles (for monocular viewing) was switched from opaque to translucent via an external trigger operated by one of the researchers. Once the trial was completed, the LCD goggles switched again to opaque. Head or gaze movements were not controlled or monitored, and participants were not given any specific instructions about head posture before or during completion of the task.

The order of the trials was randomised so that participants did not know before the beginning of the trial whether the target and flankers would be separated laterally or in depth, whether viewing would be binocular or monocular, whether the smaller or larger diameter target was to be grasped, or whether the closer or wider flanker separation was to be employed (Figure 1). This approach reduced forward planning and attempted to avoid participants becoming overly familiar with the task, which would result in vision becoming less important for task execution because participants might instead adopt a repeated/learned motor strategy[58]. In total there were 96 trials (2 target/flanker object sizes, 2 viewing conditions, 2 flanker configurations, 2 flanker spacings, with 6 repetitions for each condition) per participant.

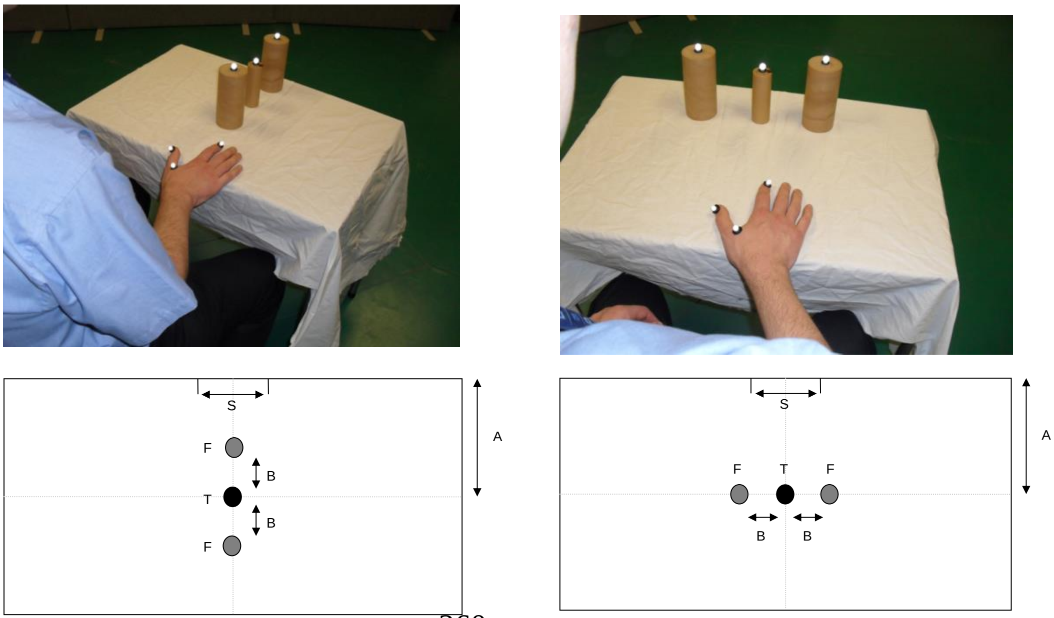

Figure 1. Photos (top) and schematic representation (bottom) of reaching and grasping task arrangement. Top: The flanker objects were cylindrical in shape and had the following dimensions: 15cm length by 5cm diameter, or 15cm length by 7cm diameter. The object to be grasped was made from medium density fibreboard. It had a height of 12cms and was either 3 (mass 85g) or 4 cm (mass 145g) in diameter. Note that a reflective marker was

also worn on the wrist (not shown in the photo). Bottom: The target object (T) was placed at a distance equivalent 66% of participant's full reach (A). The starting position of the hand for each trial is defined by the area S. Flanker objects (F) were placed either side or in front and behind the target object. The distance between the flanker and target objects varied by a distance equivalent to the width of 2 or 4 fingers (B) of each individual participant.

Instructions to participants

Participants were instructed to complete the prehension task in one natural movement without making contact with the flanker objects. They were asked to grasp the object with the hand orientated so that the fingers and thumb met the object side-on (palm orientated vertically) rather than from the top of target, then to place the target in a location of their choice towards the front edge of the table, and finally to return the hand back to the starting position. They were told not to be overly concerned with where they placed the object in front of them. The starting position of the hand was defined by an area 20 cm wide located at the front, central edge of the table (Figure 1). Two or three practice trials took place to ensure that the participant understood what the task involved and that instructions were being accurately followed.

Data collection

Retro-reflective markers (diameter 9mm) were attached to the hand of each participant. Markers were placed directly onto the skin on the lateral aspect of the wrist, on the thumb nail, on the nail of the forefinger, and on the first dorsal interosseous muscle ('V' of the hand). The target to be picked up and the flanking objects had markers placed at the centre of their upper surface. Marker trajectory data were collected (at 100Hz) using an eight camera motion capture system (Vicon MX; Oxford Metrics, Oxford, UK). The system was calibrated as per manufacturer's procedures (Workstation; Oxford metrics) at the start of all new data collection sessions and calibrations were only accepted if marker locations could be reconstructed within the area of interest (approximately a 1m cube volume in front of the participant and above the table) to within <0.5mm (calibration that didn't reach such criteria were repeated). Data collection lasted approximately one hour per participant including a short rest period at the half way point. Using Vicon's Workstation software marker trajectory data were filtered (Woltring spine routine[59] with MSE filter option set to 'auto') and the 3D coordinates of each marker were then exported in ASCII format for further analysis.

Prehension Parameters & Data analysis

The impact of a flanking object on prehension has been previously studied in visual normals (e.g. [56,57,60,61]).The presence of a flanker can produce changes in the transport component (reduced peak speed, prolongation of the time spent decelerating) and in the grasp (changes to the maximum aperture, changes to when in the movement maximum aperture is displayed)[56] . These changes are typically considered as evidence that flankers act as obstacles and thus that the changes in prehension reflect an obstacle avoidance strategy. Depending on the location of the obstacle(s), other possible changes to prehension include veering around the obstacle[57] and a reduction in the speed of movement[56]. For these reasons, as well as the results of studies of prehension for isolated targets in strabismic individuals with/without amblyopia, the prehension parameters of interest were as follows:

Reach time: time from reach initiation to end of reach. Reach initiation was defined as instant the wrist's forward velocity became greater than 20mm/s. End of reach was defined as the instant when the wrist's velocity became less than 20mm/s for at least 3 consecutive frames.

Peak reach velocity: defined as the maximum forwards velocity of wrist during the reach.

Average reach velocity: average forwards velocity of wrist during the reach period.

Time to peak velocity: time of instant of maximum wrist velocity relative to reach initiation

End reach - initial contact: time from the end of the reach to initial contact with object. Initial contact was defined as instant when the object's scalar horizontal velocity became greater than 10mm/s.

Initial contact - object lift: time from initial contact of object to instant object was lifted from table. Object lift was defined as the instant when the object's vertical velocity became greater than 50mm/s.

Overall movement time: time from reach initiation to object lift.

Maximum aperture: the maximum resultant (x,y,z) distance between thumb and forefinger.

Time to maximum aperture: time of instant of maximum aperture relative to reach initiation

The reaching and grasping parameters listed above were determined from each ASCII data file using in-house software (Visual Basic).

Statistical analysis

To evaluate how well the two groups were 'matched', participant demographics (e.g. participant age) where analysed using 2-sample (unequal variance) 2-tailed t-tests.

As the target object diameter varied between 30mm or 40mm to minimise the likelihood of a repeated motor strategy being adopted by the participants, it was not treated as an independent variable. Data were analysed via random effects regression modelling (StataCorp LP, College Station, TX, USA). Each factor's (see below) main effect was always included in the modelling, whilst the interactions between factors were incorporated sequentially and their significance was determined using the likelihood ratio test. The interactions incorporated also included the 3-way interactions where 'group' was included as one of the factors. However, because of the difficulty in their interpretation, 4-way interactions were not included. Any interactions with a p-value greater than 0.05 were dropped, while any less than 0.05 were initially retained. After various iterations, and because the focus of the paper was a comparison of amblyopes versus visual normals, the final model used was the most parsimonious one explaining a particular outcome variable in which the 'main effects' of all factors were always included; group-by-other factor interactions were included if their p-values were <0.05, and other interactions (e.g. vision-by-flanker-configuration) were included if their p-values were <0.01. Over the various models for each outcome measure, there are quite a number of possible interactions not involving 'group', the inclusion of which would create significant potential for Type I error. Given that these interactions would not affect any group comparison, we only included them if their effect was non-trivial and clearly significant. It was for this reason that we applied the more conservative criterion for statistical significance of $p<0.01$ for interactions that did not involve 'group'. Furthermore, an adequate formal approach to type I error control would be highly complex in an exploratory analysis such as this, as we would need to account for the multiplicity of predictors as well as outcome measures. Given that many of the effects we report are significant at p<0.001, and are broadly consistent with work of others in the field, we do not believe a formal approach is feasible or necessary. As such, final model 'main effect' factors with a p-value of 0.01<p<0.05 were considered borderline significant; those 0.001<p<0.01 were considered 'significant'; and those p<0.001 were considered 'clearly significant' (those >0.05 were considered 'not significant').

The p-values in the text are the ones related to the specific terms from the final model used. The following factors and interaction between these factors were the ones explored via the above modelling approach:

Group: Fixed factor with 2 levels (amblyopic individuals, AM, visual normals, VN)
Viewing condition: Fixed factor with 2 levels (binocular viewing, monocular viewing)
Flanker configuration: Fixed factor with 2 levels (lateral direction, in-depth direction)
Flanker spacing: Fixed factor with 2 levels (separation of 2- and 4 finger-widths).

Since trials were fully randomised across all conditions, repetition was not included as a factor in the modelling.

Inter-trial variability was also determined for each of the parameters we investigated. Variability was derived from the standard deviation of the measures across the repeated trials. The variability in each parameter was analysed using random effects regression modelling as per the approach described above.

Results

The average age of the amblyopic (AM) group was significantly greater than the visually-normal (VN) group (p=0.0054) but the groups did not differ in relation to binocular visual acuity (p=0.14) or visual acuity of the dominant (visual normals)/better (amblyopes) eye (p=0.30) (Table 1). As expected, the amblyopic group had a significantly reduced stereoacuity (p<0.001) and poorer visual acuity in the weakereye (p<0.001). Only 6 of the 20 amblyopes had measureable stereoacuity (Table 1). To investigate if we were justified in considering the AM group as a single group, we undertook a preliminary statistical analysis in which we compared the main outcome measures between amblyopic sub-groups of those with and without measurable stereopsis, and those with and without strabismus. This analysis (random effects regression modelling) indicated that there were no significant differences for any of the nine parameters investigated between those with and without measurable stereopsis (all p > 0.08) or those with and without strabismus (all p > 0.11). We also ran the models to compare the six amblyopes (AM-6) with measurable stereopsis (Table 1) to the visual normals. All parameter estimates for the effect of group (AM-6 versus VN) are similar to those determined for the whole group (AM versus VN), and importantly the conclusions do not change (with one exception; see next section). Henceforth, therefore, all the results for the amblyopic individuals are considered together as a single group (AM group).

Prehension Differences in Amblyopes (AM) versus Visual Normals (VN): General Group differences

Group (main effect) differences for each of the reach and grasp variables can be seen by comparing the two 'hash-filled' bars and the two 'solid-filled' bars in each of the plots in Figures 2, 3 and 4. Across all conditions, the overall time taken to complete the reach and grasp action (movement initiation to target lift) was greater by an average of 103ms in the AM- compared to the VN-group (p=0.031). This may be explained by amblyopes having a lower average reach velocity (by on average 66mm/s; p=0.021) coupled with a significantly longer duration between initial contact with the target object and object-lift (by 49ms; p=0.003), compared to visual normals. Across all conditions, the AM group also displayed significantly narrower maximum grip apertures (by 8.2mm, p=0.007). There were no other reach or grasp variables for which there was a main effect of group. A similar pattern of group main effects emerged when we compared just the amblyopes with measurable stereopsis to the VN group; the only parameter for which the group main effect was no longer significant was the duration between target object contact and lift (p=0.63, compared to p=0.003 when all amblyopes were included).

Both groups show a binocular advantage and the group differences in prehension are maintained in monocular viewing

In both groups, prehension in binocular viewing exhibited small but statistically significant differences relative to monocular viewing. Under monocular compared to binocular conditions, both groups had: a slower average reach velocity (by on average 12 mm/s; p=0.015), and consequently a longer reach time (by on average 36 ms; p<0.001) and a longer overall movement time (by on average 40ms; p<0.001); an increased maximum aperture (by on average 1 mm (p=0.009); and a later time of maximum aperture (by on average 23 ms; p<0.001) (Figure 2). The only variables showing significant group-by-viewing condition interactions were peak reach velocity (p=0.001) and average reach velocity (p=0.013). These interactions indicated that, across flanker configuration and spacing conditions, a change to monocular viewing led to a small increase in peak reach velocity in the AM-group (by an average of +7mm/s) but a small decrease in the VN group (by an average -19 mm/s). There was a small reduction in average reach velocity in both groups but the reduction was marginally greater for the VN group (reduction: VN, 17mm/s; AM, 7 mm/s) (Figure 2). However, it is important to stress that the magnitude of these interaction effects is small (e.g. the decrease in peak velocity in VN from binocular to monocular represents only a 2% change). This highlights that, in general, closing one eye had more or less the same effect in the AM group as it did in the VN group, and that the group main effect differences (highlighted above) occurred irrespective of whether viewing was binocular or monocular.

Changes in Target/Flanker-Configuration differentially affected AM compared to VN participants

Figure 3 shows how, across viewing and spacing conditions, prehension was affected by flanker configuration, and how such affects were different in AM compared to VN participants. Flanker configuration had a significant effect on all parameters (end-reach to initial contact, p=0.011; other parameters, p≤0.008; Figure 3), for example the overall movement time was longer when the flankers were separated in depth relative to the target (average difference: AM 145ms, VN 130 ms; p<0.001). There were also several parameters that were significantly affected by group-by-flanker configuration interactions. These group-by-flanker configuration interaction effects, highlight that when the flankers were separated in-depth compared to laterally, both groups: took longer over the reach but the increase was bigger for the AM group (increase: AM, 107ms; VN, 77ms; p<0.001); had a longer duration between object contact and lift but the increase was larger for the AM group (increase: AM, 55 ms; VN, 34 ms; p=0.044); had maximum grasp aperture occurring later in the reach but the delay was smaller for the AM group (delay: AM, 85 ms; VN, 107 ms; p=0.009); and had a reduction in maximum aperture size but the reduction was smaller for the AM group (decrease: AM, 7.8 mm; VN, 13.8 mm; p<0.001). In addition, the time from the end-of-reach to initial contact increased in the AM group (by +16ms) for the in-depth versus lateral configuration but it decreased in the VN group (by -19ms; p<0.001). No other group-by-flanker configuration differences reached statistical significance.

Changes in Target/Flanker-Spacing had the same effect in both groups

Reducing the spacing between the target and the flankers led to systematic changes in prehension (Figure 4), but differences were consistent across groups as evidenced by the lack of any significant group-by-spacing interactions (p>0.41), and therefore the effects of target/flanker-spacing changes are not mentioned further.

Group Differences in Inter-Trial Variability

Group main effect differences, across conditions, indicate that inter-trial variability was reduced in the AM compared to VN group for the time of when peak reach velocity occurred (lower variability in AM group by on average 19 ms/s, p=0.009), for the average reach velocity (lower variability in AM group by on average 13.4 mm/s, p=0.029), and for the maximum aperture size (less variable in the AM group by on average 1.4 mm, p=0.037). Significant group-by-flanker configuration interactions, across the viewing and spacing conditions, indicate that, the increase in inter-trial variability for the in-depth compared to the laterally-spaced flanker configuration was greater for the AM group compared to VN group for when in reach maximum aperture occurred (p<0.001), and for overall movement duration (by on average 31 ms; p=0.01) and its various components (reach duration, p=0.01;

duration from end-reach to initial contact, p=0.004; and for the duration between contact and object lift, p=0.008).

A change to monocular viewing, led to a borderline significant increase in inter-trial variability in overall movement time (by an average of 11 ms; p=0.029), but all other variables were unaffected (p>0.12) by viewing condition. This was consistent across the two groups as evidenced by the lack of any significant group-by-viewing condition interactions (all p>0.08).

Discussion

Summary of Findings & Comparison with Previous Studies

This is the first study to examine prehension in humans with naturally-occurring binocular disorders where the target to be lifted was flanked; previous studies of reaching and grasping behaviour in humans with naturally-occurring disorders of binocularity [25,29,30,38,39] have featured isolated targets. Nevertheless, our findings are consistent with the results from these earlier investigations (see Grant & Moseley[40] for review) of prehension in amblyopic children [29,30] and adults[25], and in adults with strabismus without amblyopia[39], where, compared to visually normal controls, smaller maximum grasp apertures and longer overall movement times were evident, with the latter being attributable to a lower average reach velocity and a longer delay between initial contact with the target and the instant of target lift.

The increased time by amblyopes from initial contact to object lift (p=0.003) indicates that amblyopes were poorer, by comparison to visually normal participants, at coordinating the grasp with the initiation of object lift. The longer time from initial contact with the object to object lift in amblyopes suggests that they had poorer visual information regarding where their hand was relative to the object, and that they had to rely more on somatosensory feedback from the fingers and/or thumb about when exactly contact with the object had been made before they then finalised the grasp and lift. This is consistent with Melmoth et al. [39] who suggested that individuals with strabismus may place greater reliance on non-visual (e.g. tactile, kinaesthetic) feedback from digit contact with the target for the coordination of the grasp. Previous studies also report that those with poor binocularity have more frequent reaching and grasping errors than visual normals[25,29,30,38,39].

Our amblyopic participants did not display more gross errors [collisions], as fewer than 1% of trials (in normals and amblyopes) featured the target or flanker objects being knocked over. Although this suggests a clear difference relative to previous studies, 'errors' in these previous studies were defined in various ways: for example in relation to the reach, as late velocity corrections, collisions with the object and corrections in the trajectory towards the object; and in relation to the grasp, as adjustments to grip aperture before contact and during grip application, and prolonged grip applications. Our measures of the time from end reach to initial contact, and from initial contact to object lift, are analogous measures of such 'errors'. The overall pattern of differences that we, and others[25,29,30,38,39] have observed indicates a more cautious, uncertain and more careful prehension behaviour by individuals with amblyopia, as evidenced by a lower average velocity, longer overall movement time, and reduced variability of maximum grip aperture and average velocity, in comparison to visual normals. They also became more cautious/uncertain yet more variable for the condition where the flanker objects were separated in-depth, as opposed to being laterally spaced. Our results are thus also generally consistent with findings that amblyopic children[27] and adults[26] perform worse than controls on non-prehension tasks requiring fine motor control, particularly when speed and accuracy are required.

The task completed by our participants shares some similarities with those in studies of obstacle avoidance conducted in visual normals[56,60]. Indeed, the kinematic patterns which we observed in both our groups, particularly for in-depth target/flanker configuration, are consistent with the changes to the transport and grasp formation elements of the reach-to-grasp movements for non-isolated targets previously reported[56,57,60,61] [see Introduction above], and hence with their interpretation as reflecting an obstacle avoidance strategy [56].

Amblyopes show a similar binocular advantage compared to Visual-Normals and the amblyopic deficit persists in monocular viewing

For the group differences in prehension, the pattern and magnitude of the deficits was similar regardless of whether viewing was binocular or monocular. Since binocularity is markedly reduced in amblyopia[7,8,10,11], one might expect that switching from binocular to monocular viewing would have less of an effect than in visual normals. However, this is not what we, or Suttle et al. [30] or Grant and Conway[38] (high-contrast condition) found, although as indicated above this surprising finding is at odds with the findings from other studies[25,29,39]. The origins of these between study differences are not obvious but they may relate to differences in ages between participants, or differences in the depth of amblyopia or extent of residual binocularity. We now consider different possible explanations for our finding that the binocular advantage exists in amblyopes to the same extent as in normals. Interestingly, it has been suggested that the role of binocular vision in prehension is to contribute to the development underlying visuomotor skill acquisition during normal maturation[29,30]. If this is correct, it would provide a potential explanation for why poorer performance amongst amblyopes transfers to monocular viewing conditions.

Considerable Residual Binocularity or Differences in Task Strategy amongst Amblyopic Participants?

When one eye is closed, binocular disparity is eliminated, vergence cues are greatly diminished, there is a reduction in the overall size of the field of view, and for dynamic scenes there is no opportunity to compare patterns of optic flow between the eyes. For the task in the present study, the target was in the central field and both the target and participant were static (although head movements were not restricted). The elimination of binocular disparity and vergence cues are the most important factors to consider when considering prehensile movements executed with one eye. The fact that the binocular advantage was similar in our amblyopic and visually-normal groups suggests that two eyes are better than one when it comes to prehension, not only in visual-normals but also in amblyopes. This, in turn, suggests that there is considerable residual binocularity in amblyopes, or that amblyopes are able to make very good use of whatever binocularity they have. There is evidence that the level of binocularity in amblyopic individuals may be underestimated by standard clinical vision testing[62-67] and this would be consistent with the view that binocularity is important for prehension. Binocularity may potentially be important because motion-in-depth vision should be particularly useful for guiding hand movements. A different interpretation of our finding that the binocular advantage is similar in amblyopes and in visual-normals is that, despite substantially degraded binocularity, individuals with amblyopia are able to make use of whatever binocularity they have left, perhaps using different strategies or cues. We didn’t restrict or monitor head movements and although there was no obvious variation between participants in the strategy they used to complete the task, we are unable to rule this out. Thus we are not in a position to be able to distinguish between the residual-binocularity and different-strategy hypotheses.

Amblyope versus Normal differences: more apparent for the In-Depth Configuration

Since individuals with amblyopia generally exhibit grossly reduced binocularity[7,8,10,11] and given the claims that the magnitude of deficits in reaching and grasping in amblyopes are related to the extent of the reduction in binocularity[25,29,30,38], we hypothesised that deficits in prehension would be exaggerated for the in-depth relative to the lateral-separation configuration. Consistent with this hypothesis, we did find evidence for additional differences in prehension between amblyopes and visually normal participants when the target and flankers were separated in-depth, as evidenced by several parameters returning significant group-by-direction interactions. For the in-depth versus lateral-spaced configuration, compared to visual normals, our amblyopes displayed a smaller decrease in maximum aperture, a smaller delay in time to maximum aperture, and a larger increase in reach time and time from initial contact to object lift. Amblyopes also displayed greater inter-trial variability for the in-depth versus lateral-spaced configuration in reach duration, in end reach to initial contact, in initial contact to object lift, and in the overall movement time. In addition, greater variability amongst amblyopes for the in-depth configuration was evident for the instant in the reach when maximum aperture occurred. We interpret greater variability across repetitions as evidence of increased uncertainty about target and flankers [size and location] and about the location of the hand relative to these objects.

When grasping the object that was flanked in the in-depth direction, participants moved their fingers and thumb medially towards the target at the end of the reach and in doing so would have had to determine the (depth) position of their fingers relative to the rear flanker and target object, and the position of their thumb relative to the front flanker and target object. In contrast, when grasping the object when it was laterally flanked, determining the relative depth position of the fingers, thumb, target-object and flankers was much less important because the fingers and thumb were 'slotted' either side of the target as the hand was moved forwards. This highlights that more (richer) relative depth and position information was required for the in-depth compared to laterally-spaced configuration. Hence the increased deficits in prehension for amblyopes, compared to visually normal participants for the in-depth configuration suggests that amblyopes were unable to make use of these rich binocular cues to the same extent as was the case in visual normals.

A Special Role for Binocular Vision in Prehension?

The evidence from our study and from several previous studies of visual normals indicates that prehension in monocular viewing is altered compared to that under binocular conditions[25,29,42,68]. However, the differences between binocular and monocular performance that we and others have observed are relatively modest in magnitude, suggesting that while binocular vision is important for prehension, it may not be crucial. Although, past research has suggested an important role for binocular vision in prehension[42-44], it now seems likely that there may not be a special role for binocular information for the execution and control of grasping[50-52]. According to this view, both monocular and binocular depth cues are important in the programming of grasping. Thus, binocular vison is important for prehension, but only in the sense that it provides additional cues. Whenever additional cues are available, the system attaches differential weights to each cue[53-55]. More cues mean less perceptual uncertainty and minimising uncertainty is an important goal. Thus, in this framework, the effects on prehension of removing (or already having lost) binocular vision stem not from the loss of critically important information, but from an increase in uncertainty.

The idea of monocular and binocular cue-combination as it applies to prehension has been in existence for a considerable time (e.g.[47]) but it has recently gained more credence having been subjected to a formal evaluation by Keefe et al.[51] who developed a paradigm to selectively remove either monocular cues or binocular cues. They showed that removing either type of cue resulted in similar changes to grasping behaviour, specifically larger maximum grip apertures resulted. Keefe et al.'s[51] data argue against a binocular specialism for grasp programming because maximum grip apertures were smallest when both monocular and binocular cues were available and smaller grip apertures indicate less uncertainty from integration of the information from all of the available cues.

In the present study, both monocular and binocular cues differed in the two target-flanker configurations. While binocular cues are richer for the in-depth compared to the laterally-spaced target/flanker configuration, there are a number of additional monocular cues to depth in the in-depth configuration, including occlusion and height-in-scene information[69]. The greater differences between the amblyopes and visual-normals for the in-depth versus the laterally-flanked configuration suggests that in the amblyopic group these monocular cues attracted less weighting compared to the binocular cues, or amblopes had an inability to make full use of the binocular cues available. However, the fact there was a similar binocular advantage in amblyopes and visual normals suggests that amblopes have considerable residual binocularity or they are able to make full use of whatever little binocularity remains.

Limitations of our study

It would have been useful to have included a no-flanker condition as this would have allowed us to determine whether the presence of flanker objects, irrespective of configuration, had a differential effect in amblyopes versus visual normals. We used the Frisby test to determine the level of stereoacuity. Had we used additional tests we may have revealed levels of binocular co-operation in the fourteen participants who achieved no result on the Frisby test. We didn't monitor head movements so we cannot say whether some participants used different cues or subtle changes in strategy to execute the task. Hand starting position was not fixed and it is thus possible that some of the variability differences across groups and/or conditions was related to the hand starting in a slightly different location across the repeated trials. However, such variability would likely have been similar across the different conditions and thus we do not believe it had any bearing on the results presented. Another limitation is that the pattern of results we obtained could be a consequence of the instructions we gave to our participants about how the task was to be executed. For example, if the task had been to pick up the object as quickly as possible as opposed to allowing participants to complete the task in their own time, we might have revealed a bigger effect of amblyopia, or of the target-flanker configuration, or of switching to monocular viewing. Perhaps this is not a limitation as such but an avenue for future research because others have found that amblyopic deficits are more pronounced when speed or accuracy is emphasised (e.g. [27]).

Clinical implications of our findings

There is evidence linking the magnitude of prehension deficits to the presence or absence of binocularity[25,29,30,38,39], and there are many claims that at least some binocularity can be recovered in individuals with amblyopia[70,71], even in adults[72-74]. Thus, even though the present study highlights that binocular vision is not paramount for the control of reaching and grasping, the fact that there was a significant advantage in amblyopes under binocular viewing (as there was in visual normals), is something that can be used to argue for therapy aimed at recovering binocularity in individuals with amblyopia. Interestingly, evidence that improvements in binocularity following treatment are linked to changes in functional aspects of visuomotor control such as prehension has just started to appear in the literature[29].

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Figure Legends:

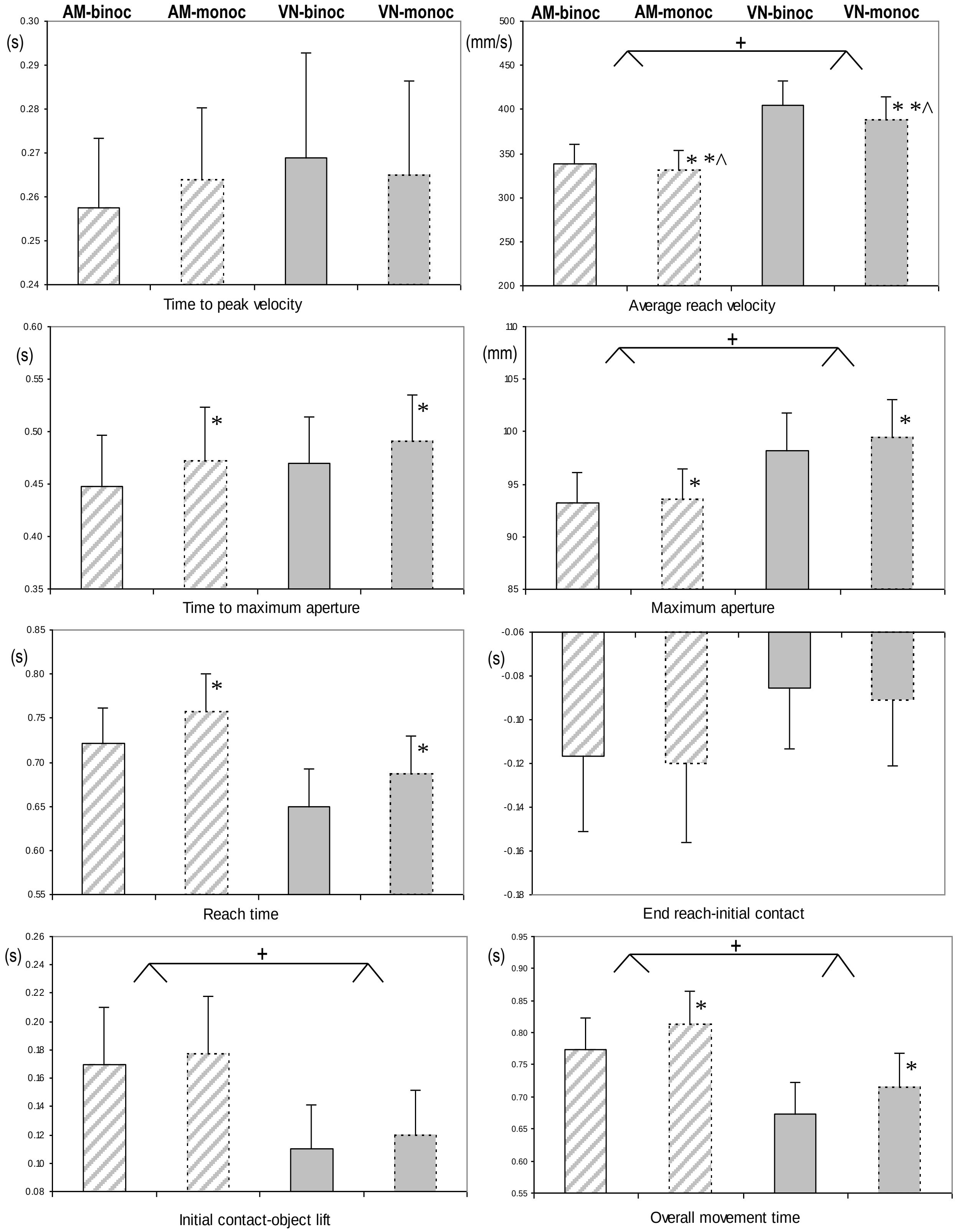
Figure 1: Figure 1. Photos (top) and schematic representation (bottom) of reaching and grasping task arrangement. Top: The flanker objects were cylindrical in shape and had the following dimensions: 15cm length by 5cm diameter, or 15cm length by 7cm diameter. The object to be grasped was made from medium density fibreboard. It had a height of 12cms and was either 3 (mass 85g) or 4 cm (mass 145g) in diameter. Note that a reflective marker was also worn on the wrist (not shown in the photo). Bottom: The target object (T) was placed at a distance equivalent 66% of participant's full reach (A). The starting position of the hand for each trial is defined by the area S. Flanker objects (F) were placed either side or in front and behind the target object. The distance between the flanker and target objects varied by a distance equivalent to the width of 2 or 4 fingers (B) of each individual participant.

Figure 2. Mean (+/- SE) reach and grasp parameters for the amblyopic (AM, hashed bars) and visual normal (VN, solid bars) groups in binocular (binoc, solid line) and monocular viewing (better eye in amblyopes, or dominant eye in visual normals) (monoc, dotted line). Data are averaged across 'flanker' configuration and spacing conditions. + indicates group differences ($p<0.05$), * indicates viewing condition main effect ($p\leq0.015$), and *^ indicates group-by-viewing condition interactions ($p=0.013$). Peak reach velocity data (not shown) conform to pattern of results for average reach velocity.

Figure 3. Mean (+/- SE) reach and grasp parameters for the amblyopic (AM, hashed bars) and visual normal (VN, solid bars) groups for the lateral flanker (lat, solid line) and in-depth flanker (dep, dotted line) configurations. Data are average across viewing and spacing conditions. + indicates group differences ($p<0.05$), * indicates flanker configuration main effect ($p\leq0.01$), and *^ indicates group-by-flanker configuration interactions ($p<0.05$). Peak reach velocity data (not shown) conform to pattern of results for average reach velocity.

Figure 4. Mean (+/- SE) reach and grasp parameters for the amblyopic (AM, hashed bars) and visual normal (VN, solid bars) groups for the two finger (2f, solid line) and four finger (4f, dotted line) spacing conditions. Data are average across viewing and 'flanker' configuration conditions. + indicates group differences ($p<0.05$), and * indicates spacing main effect

(p≤0.01). There were no significant group by magnitude-of-spacing effects. Peak reach velocity data (not shown) conform to pattern of results for average reach velocity.



AM-binoc
AM-monoc
VN-binoc
VN-monoc
(s)
Time to peak velocity
(mm/s)
Average reach velocity
Time to maximum aperture
(mm)
Maximum aperture
Reach time
End reach-initial contact
Initial contact-object lift
Overall movement time

Figure 2

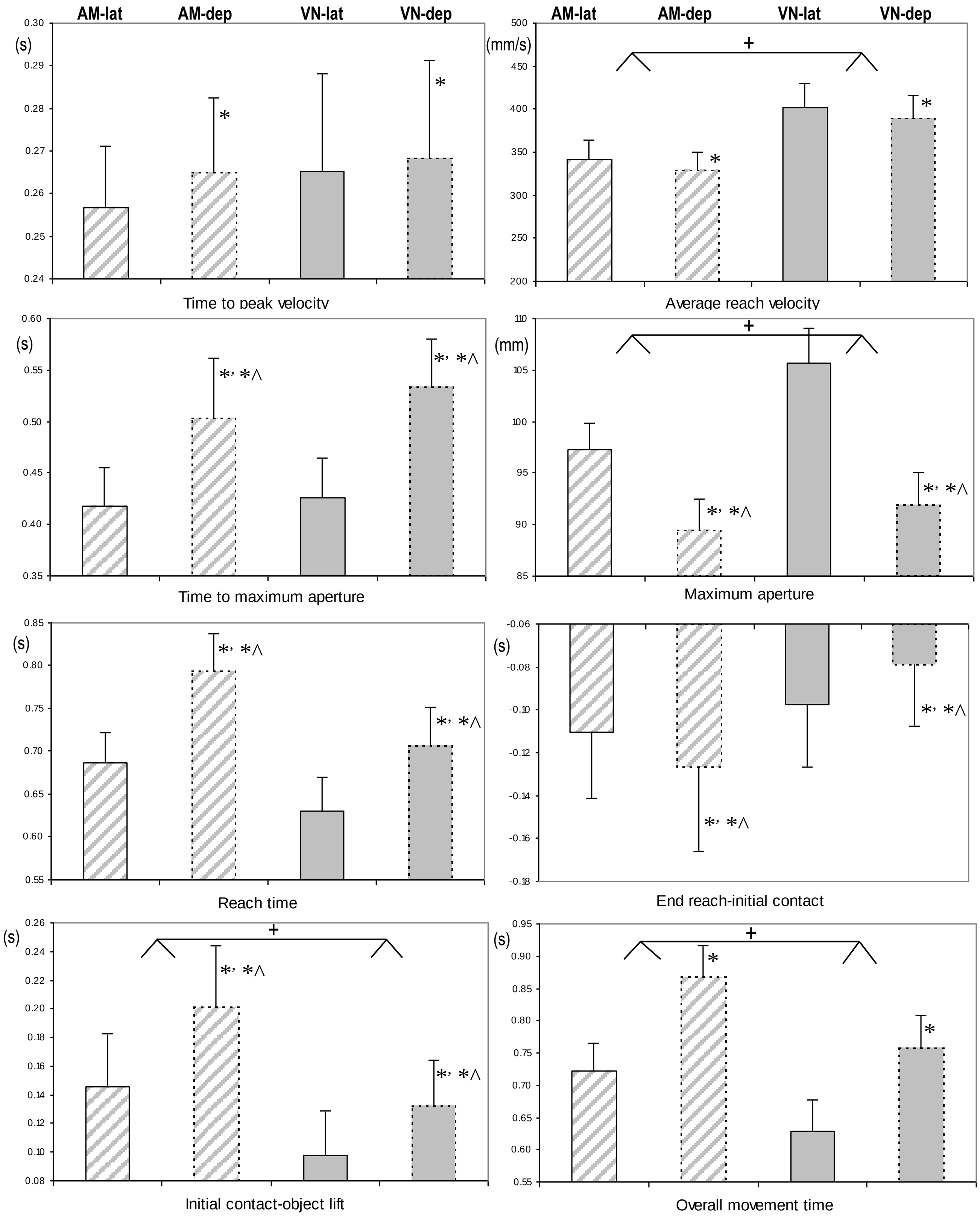

AM-lat
AM-dep
VN-lat
VN-dep
(s)
0.30
0.29
0.28
0.27
0.26
0.25
0.24
Time to peak velocity
(mm/s)
500
450
400
350
300
250
200
Average reach velocity
(s)
0.60
0.55
0.50
0.45
0.40
0.35
Time to maximum aperture
(mm)
110
105
100
95
90
85
Maximum aperture
(s)
0.85
0.80
0.75
0.70
0.65
0.60
0.55
Reach time
(s)
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
End reach-initial contact
(s)
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
Initial contact-object lift
(s)
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
Overall movement time
*
+
*, *^

Figure 3.

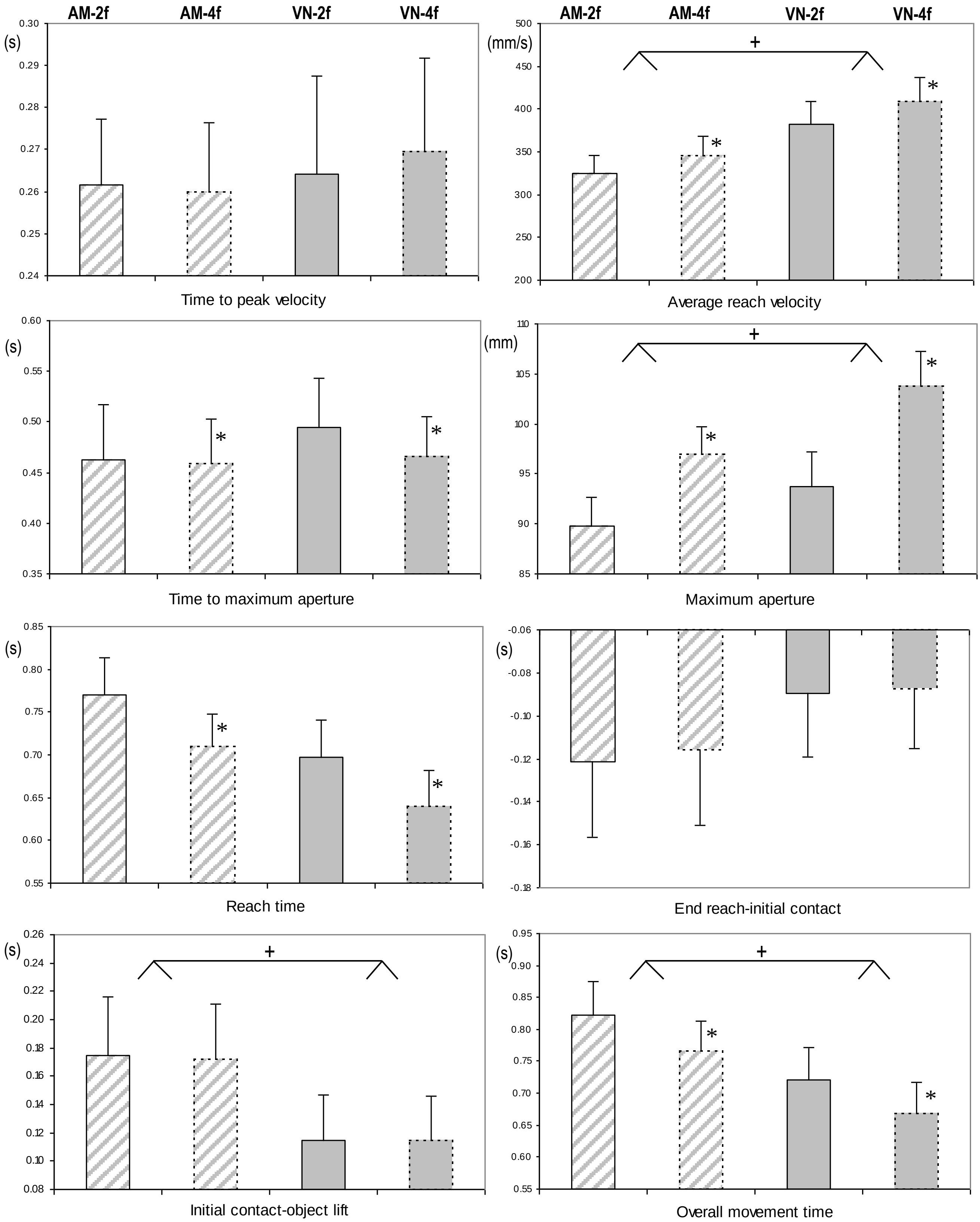

AM-2f
AM-4f
VN-2f
VN-4f
(s)
Time to peak velocity
(mm/s)
Average reach velocity
(s)
Time to maximum aperture
(mm)
Maximum aperture
(s)
Reach time
(s)
End reach-initial contact
(s)
Initial contact-object lift
(s)
Overall movement time

Figure 4.

Table 1: Clinical characteristics of amblyopic paticipants.

Participant No.	Age(years)	Amblyopic Eye	Rx Worn?	Habitual VA (AE)	Habitual VA (FE)	Habitual VA (Binoc)	Strabismus?	Stereoacuity (secs arc)
1	41	L	Nil	1.40	-0.10	-0.10	LXOT	---
2	50	R	RE: -2.75/-0.75x180, LE: -5.50DS	0.26	-0.02	-0.04	No strabismus	60
3	36	L	RE: +9.00/-2.00x25, LE: +8.00/-2.25x180	0.84	0.10	0.08	LSOT, R/L	---
4	43	L	RE: plano/-1.25x9, LE: -2.75/-0.25x170	1.50	-0.10	-0.10	LXOT, R/L	---
5	54	L	RE: +0.50/-1.50x175, LE: +2.00/-4.00x11	0.94	-0.10	-0.10	LXOT	---
6	42	L	RE: +2.00DS, LE:+2.00DS	0.20	-0.20	-0.24	LSOT	---
7	30	L	Nil	0.86	-0.06	-0.10	No strabismus	---
8	23	R	RE: -4.50/-0.75x90, LE: -1.50/-0.25x180	1.00	-0.10	-0.10	LXOT	---
9	22	R	RE: +1.25/-3.50x180, LE: -0.50/-0.25x10	0.30	0.00	-0.06	No strabismus	170
10	36	R	RE: +2.50/-0.50x100, LE: +0.75/-0.50x30	0.20	0.00	-0.04	RSOT	---
11	29	R	RE: +2.75/-0.25x90, LE: +0.50/-0.25x90	0.20	0.00	-0.02	No strabismus	170
12	40	L	RE: +6.25/-0.50x55, LE: +6.75/-1.00x155	0.70	-0.20	-0.20	LSOT	---
13	66	R	RE:+3.75/-0.25x70, LE: +1.00DS	0.80	0.08	0.04	RSOT	---
14	27	L	RE: +1.25/-0.50x120, LE: -3.50/-1.50x25	0.20	-0.10	-0.10	LXOT, R/L	---
15	46	R	Nil	0.50	0.00	0.00	No strabismus	85
16	37	L	RE: +0.50/-2.00x17, LE: +2.00/-1.75x5	0.36	0.10	0.04	LSOT	---
17	24	R	RE: +1.50DS, LE:+1.50DS	0.30	0.00	0.00	RSOT	600
18	28	L	RE:+0.50/-0.50x175, LE: +3.75/-1.00x165	0.44	-0.08	-0.06	LSOT	---
19	33	R	RE: +2.00DS, LE:-1.00DS	0.60	-0.04	-0.10	RSOT	---
20	21	R	RE: +1.00DS, LE:+0.25/-1.00x105	0.26	0.00	0.00	No strabismus	85
Average (Amblyopes)	***36.4±11.7***			***0.59±0.40***	***-0.04±0.08***	***-0.06±0.08***		***--***
Average (Visual Normals)	***27.5±6.3***			***-0.05±0.07***	***-0.05±0.08***	***-0.10±0.08***		***31.1±14.6***

Visual acuity (VA, all in logMAR notation)was measured using a PC-based system (Test Chart 2000, www.thomson-software-solutions.com) at a testing distance of 3 metres and a per-letter scoring system.

VAs were measured under binocular (i.e. both eyes open) and monocular conditions with the participant's habitual refractive correction in place

AE: Amblyopic eye; FE: fellow eye; DS: Dioptre sphere; RE: Right; LE: Left; Binoc: Binocular; XOT: exotropia; SOT esotropia; R/L: R hypertropia; Stereoacuity was measured using near Frisby stereotest.

---' means stereoacuity was not measurable. Habitual VAs (FE, AE, Binoc) represent VA exhibited by participants in the conditions in which we assessed prehension.