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SYMPOSIUM PROCEEDINGS

Amblyopia and Real-World Visuomotor Tasks

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ABSTRACT

A question of increasing interest to the basic science and clinical management communities during the past decade is whether children and adults with amblyopia and associated binocular visual abnormalities experience difficulties in executing real-world actions, to which vision normally makes an important functional contribution. Here we provide objective evidence that they do, by reviewing quantitative data from a number of studies comparing their performance with that of matched normally sighted subjects on a range of everyday visuomotor tasks. Because in real life, these tasks (grasping objects, walking, driving, reading) are habitually performed with both eyes open, our focus is on their binocular skill deficits, rather than those with their amblyopic eye alone. General findings are that individuals with abnormal binocularity show impairments in critical aspects of motor control—movement speed, accuracy or both—on every one of these activities, the extent of which correlates with their loss of stereoacuity, but not the severity of their amblyopia. Impairments were especially marked when the task was time-limited or novel. Implications are that children and adults with severely reduced or absent binocularity may be accident-prone when required to respond rapidly to unexpected situations and that amblyopia management should focus more attention on evaluating and restoring stereoacuity and stereomotion processing.

Keywords: binocular vision, stereoacuity, eye-hand coordination, driving, gait, reading

INTRODUCTION

"*Considering the tremendous scientific effort expended on understanding amblyopia and its clinical management, the lack of research on its functional impact is simply stunning and is a sad reflection of the level of interaction between basic and clinical science.*" (Fielder, 2002).

This trenchant viewpoint succinctly expresses how, up until only a few years ago, we lacked any real understanding of the extent to which amblyopia impacts on the everyday activities of those with the disorder. This starkly contrasted with our knowledge of perceptual deficits observed in the laboratory on a wide range of spatial visual tasks (eg, visual, grating, alignment and stereo acuities, contrast sensitivity, contour integration, global motion perception), which could be fairly judged as extensive (see Hess, 2002). Some impetus to bridging this knowledge gap had already been generated by those of the opinion that the absence of any data that amblyopia results in disablement undermined the rationale for screening for the condition and even for its treatment (see Snowdon & Stewart-Brown, 1997). Now, less than 10 years since Fielder remarked upon the "stunning" lack of research on functional impact, a significant body of empirical evidence has accumulated on daily encountered "real-world" tasks, each having a significant visual component. Here we review studies of eye-hand coordination, walking, driving, and reading skills, which have formed the bulk of basic research in this area, and evaluate the impairments that children or adults with amblyopia exhibit on such tasks.

The visuomotor control of real-world actions generally involves at least three essential processes (see Milner & Goodale, 2008). First, visual perceptual information relating to the extrinsic (eg, distance, velocity) and intrinsic (eg, size, depth, weight) properties of any target object and of the surrounding environment (including potential obstacles) is employed to plan the desired movements before they begin. This planning phase is thought to involve conscious or "pre-conscious" selection of the most appropriate course of action, which can be strongly influenced by cognitive factors including

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past experience (eg, eggs are fragile and need to be handled with care), and to be mediated by the "ventral" (occipitotemporal) cortical processing stream. Next, the selected plan engages "dorsal" stream areas of posterior parietal and/or premotor cortex, concerned with the more automatic programming and control of the timing and metrics of the movements required for their skilled implementation. Since perceptual processes tend to be inaccurate due to inherent uncertainties, ambiguities, or biases, motor programs almost invariably contain errors (see Lee et al., 2008), while movements themselves generate "noise" in the motor system. For these reasons, visual monitoring of the movement in progress via fast feedback processes is typically employed to generate "on-line" corrections that significantly enhance movement speed and precision.

Following Fielder's (2002) remarks, there is now convincing evidence of abnormalities in structure and function within the vision-for-perception and vision-for-action cortex of people with amblyopia (Anderson & Swettenham, 2006; Lerner et al., 2003; Mendola et al., 2005; Muckli et al., 2006; Yan et al., 2010) and for less effective communication between the two streams (Li et al., 2011). It should, therefore, come as little surprise that amblyopes exhibit a range of visuomotor impairments, especially when using their affected eye (eg, Grant et al., 2007) when its visual acuity (VA) loss is "moderate" (eg, logMAR 0.5-1.0) or "severe" (eg, logMAR >1.0). Such use does not, however, accord with real experience in daily life, in which tasks are habitually performed with both eyes open. Amblyopia is invariably associated with abnormalities of binocular depth vision. Indeed, we have sympathy with the argument that loss of binocularity is the primary problem accompanying early eye misalignment (strabismus), refractive imbalance (anisometropia), or image deprivation. Moreover, there are suggestions from both behavioral (Knill, 2005) and functional imaging (Verhagen et al., 2008) studies that binocular depth cues are accorded more weight by the action-control than perceptual processing streams.

Our review, therefore, emphasizes impairments in binocular task performance. There are several recurring themes: (1) In developmentally normal subjects, two eyes are nearly always much better than one for performing real-world actions, regardless of whether the task has an obvious depth or 3-dimensional (3D) component or not (eg, drawing, reading). (2) The binocular visuomotor control of amblyopic subjects is generally worse on the critical measures of task performance—that is, slower, less accurate, or both—than that of normally sighted controls, and tends to deteriorate in correlation with their loss of depth vision (ie, stereoacuity) rather than severity of amblyopia. (3) One reason for this is that their performance when employing only the "fellow" or "sound" eye alone, even in older amblyopes with no measurable binocularity, is generally no better—and sometimes, actually worse—than that of the dominant (sighting) eye of normal adults. This argues against the widely held idea that, via the repeated use of numerous alternative monocular sources of visual information, people without binocular stereovision will eventually adapt to their condition without detriment to their visuomotor abilities. Indeed, contrary to the "spare-eye" hypothesis (eg, Philips, 1987), which maintains that there are only limited functional benefits of possessing two eyes, objective evidence now supports the personal experience of many people who have lost vision in one eye that, as summarized by Godber (1987): *"To the one-eyed golfer, all greens are flat"*.

EYE-HAND COORDINATION

Eye-hand coordination skills for reaching out to accurately grasp and manipulate real-world objects involve a series of actions that are critically influenced by visual information about the 3D properties of the target and of the near-space environment in which it resides. Numerous studies have demonstrated that normal adults perform these actions with increased speed and precision when using binocular compared with monocular vision (reviewed in Melmoth & Grant, 2006). Several experiments have also manipulated the nature of the binocular information available to normal adult subjects—by selectively altering vergence, concordance or disparity cues—while they plan and execute reach-to-grasp movements towards stationary or moving objects (Bennett et al., 2000; Bingham et al., 2001; Bradshaw et al., 2004; Melmoth et al., 2007; Mon-Williams & Dijkerman, 1999). A general finding is that vergence contributes to distance judgments for reach planning, while disparity information concerning 3D object properties and changes in relative hand-target depth underlie the typical binocular advantages for controlling temporal (speed) and spatial (accuracy) aspects of the grip.

Successful Completion of Practical Tasks

Three studies have appeared since 2002 reporting the effects of amblyopia and reduced binocular depth vision on a range of practical eye-hand coordination skills (Hrisos et al., 2006; O'Connor et al., 2010; Webber et al., 2008). Each study involved relatively large numbers of subjects, including matched normally sighted controls, and—coincidentally—at successive stages of development; from pre-school (3–5 years old) through early school-age children (≈6–10 years), to participants aged 10–30 years, respectively. Subjects generally performed the tests with their preferred hand and with both eyes open, as would be typical in daily life, with their abilities assessed by outcome measures of successful task completion. All 3 studies incorporated tests of manual speed-dexterity involving bead-threading (on a shoelace or needle) and moving pegs in or out of a board, in which success was evaluated by the total number of items moved within a fixed time period or by the time taken to complete a fixed number of movements. In addition to these time-limited 3D tasks, Hrisos et al. (2006) and Webber et al. (2008) included a series of separate tests requiring their children to draw or copy different 2D shapes, the main constraint being for accuracy, as determined by the number of errors produced.

Hrisos et al. (2006) examined 28 mild-to-moderate pre-school amblyopes (logMAR equivalent 0.2–1.0 in their affected eye), all of non-strabismic etiology, most of whom had abnormal stereoacuity (>70 arc secs). Webber et al. (2008) studied 82 amblyopic children with interocular acuity differences (IODs) >0.2 logMAR. Their affected participants had a variety of strabismic and non-strabismic causes, with the majority (≈60%) having no measurable (nil) stereopsis and most of the others reduced or "coarse" stereoacuity thresholds (up to 800 arc secs). A similar mixture of causes, VA, and stereoacuity deficits were present among the older subjects examined by O'Connor et al. (2010).

Common findings were that affected participants performed worse on most of the tests—and never better—than the normal controls, their poorer abilities being more evident on the time-limited 3D speed-dexterity tasks than on those that emphasized accuracy in 2 dimensions. Further analyses showed that performance on the affected tasks deteriorated across participants in direct association with their reduced binocular stereovision, but not with the vision losses in their non-dominant/amblyopic eye. For example, Hrisos et al. (2006) found a moderate correlation between the amblyopic eye VA and stereoacuity thresholds of their pre-school children (Pearson's r = 0.53) and, in a regression model, that their reduced binocularity significantly *predicted* their bead-threading and 2D design copying scores (both r≈–0.35) whereas their depth of amblyopia did not. As a further example, O'Connor et al. (2010) recorded successively longer average times of 49, 52.5, and 58 secs for their subjects with normal stereovision (n = 87), coarse (n = 14), and negative (n = 20) stereopsis (according to the Preschool Randot stereotest) to thread a fixed number of large beads on a needle. These findings thus suggest that while optimal eye-hand coordination requires high-grade stereovision, the presence of residual binocularity may be better than none at all.

These latter authors also tested the speed-dexterity skills of each participant under monocular conditions (subjects chose which eye to use), and obtained mean times of 65 secs for the controls, but a significantly shorter time of 58 secs (again) for those with nil stereopsis on the same large-bead threading task (O'Connor et al., 2010). That is, the performance with both eyes open of the subjects with long-term absence of measurable binocularity appeared to be dictated by their (presumably) dominant eye abilities, which on this—although not the pegboard (O'Connor et al., 2010) task—showed an improvement over that of normally sighted participants forced to temporarily use one eye. To our knowledge, this is the only reported evidence of enhanced dominant eye visuomotor function in stereo-deficient subjects.

Reaching to Precision Grasp Stationary Objects

Others have taken a different approach to evaluating the eye-hand coordination skills of amblyopic children (Suttle et al., 2011) and adults (Grant et al., 2007), involving objective analyses of their movement kinematics. That is, this work investigated detailed spatial and temporal features of the hand movements produced by subjects with the disorder, rather than their overall success. Participants performed similar and rather simple, repetitive tasks. Using both eyes together or their dominant or non-dominant eye alone, they had to reach out and use a precision (thumb-index finger) grip to pick up and move a single, high-contrast, spatially detailed cylindrical household object, which varied in size and location between trials. Various kinematic parameters related to the planning and execution of the reach and the grasp were quantified, along with any errors or corrections occurring in their execution on each trial, from recordings of the 3D motion of infra-red reflective markers attached to the preferred hand. Subjects were matched in each experiment to visually normal controls of similar dominant eye logMAR VA, age, sex, and handedness. The children (n = 21) were aged 4–8 years, had strabismus and/or anisometropia, and logMAR IODs ranging from 0.12–1.10, indicative of mild to severe VA losses; 11 had no measurable stereopsis, with 10 having stereoacuity thresholds of 55–3000 arc secs. The adult (n = 20) participants (aged 19–48 years) were also a mixture of strabismic and non-strabismic amblyopes with mild-to-severe VA deficits, 7 of whom had coarse stereopsis (120–3000 arc secs).

The major finding of Suttle et al. (2011) was that the performance of the children with amblyopia was uniformly poor and worse than the controls on parameters reflecting both movement speed and accuracy under all three viewing conditions, including, most surprisingly, with their sound/dominant eye. In general, the amblyopic children programmed slower (ie, more cautious) movements than the normal subjects and they spent almost twice as long in the final approach to the objects at the end of the reach and in closing and applying their grip, resulting in significantly prolonged movement execution times (Figure 1). They also made many (1.5–3 times) more spatial errors in planning their reach direction and in initially positioning their grip on the objects than the normal children, which they more commonly attempted to rectify—though not always successfully—by overt corrections to their movements on-line. These latter deficits showed a more

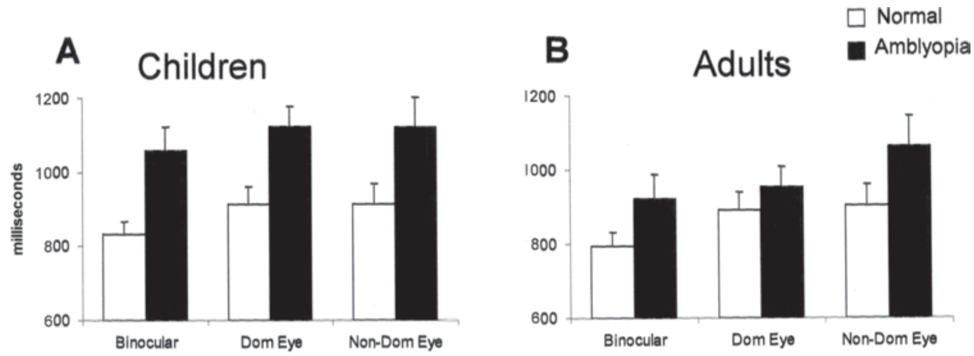

FIGURE 1 Average movement execution times (in milliseconds), from the start of the reach to object lifting at the end of the grasp, in (A) children and (B) adult subjects, with (filled histograms) and without (unfilled histograms) amblyopia, as a function of viewing condition. Errors bars, SEM.

consistent relationship with their reduced binocularity than accompanying depth of amblyopia. For example, grasping error rates were significantly increased under all viewing conditions in the participants with nil stereoacuity, irrespective of their IODs, compared with those with coarse or normal stereopsis. This finding suggests that the absence of stereovision impairs initial learning of grasping skills (c.f., Mazyn et al., 2007, below), a problem that translates to monocular performance.

Adults with amblyopia exhibited many, though not all, of the same deficits versus controls (Grant et al., 2007) as were present in the children. Most importantly, their binocular movement execution times were significantly prolonged (Figure 1), due to similar hesitancies and errors in the final reach and grasping phases of the movement, these impairments, again, being more marked in those with the worst stereoacuity. However, the impairments when using both eyes also co-varied with the severity of their VA losses, as did similar deficits in their amblyopic eye performance. The other notable differences were that the adults moved faster than the children, particularly when they were amblyopic, and that the affected adults no longer exhibited obvious deficits in their dominant eye performance (Figure 1). This suggests that children with amblyopia can eventually improve their eye-hand coordination skills, perhaps via enhanced action planning acquired through repeated sensory (perceptual) or motor experience, consistent with evidence that cognitive and visuomotor skills normally continue to mature well into adolescence (see Suttle et al., 2011).

Nonetheless, the presence of binocular stereovision appears essential for the normal acquisition of precision grasping skills (Grant et al., 2007). More compelling evidence for this was obtained in a similar kinematic study (Melmoth et al., 2009) of the reach-to-grasp performance of 20 strabismic and/or anisometropic adults (aged 19–35 years) with normalized (“cured”) VA in their amblyopic eye following childhood therapy, but with persistently reduced (n = 10) stereoacuity (100–3000 arc secs) or nil (n = 10) stereopsis. Once again, binocular movement times and spatial errors in initial grip placement were significantly increased in these subjects compared with matched normal controls, although reach durations were less affected. Further analysis showed that the increased execution times were largely attributable to the stereodeficient subjects prolonging (by ≈25%) their time in contact with the objects and adjusting their grasp before picking them up. Melmoth et al. (2009) interpreted these effects as a long-term adaptation to the subjects’ stereo loss, whereby they reduce their dependence on visual hand-target depth information towards the end of the reach, while placing greater reliance on non-visual (eg, tactile, kinesthetic) feedback from digit-contact with the objects for the control of grip precision and stability.

Reaching to Grasp Moving Objects

Successful interception of moving objects depends on visual motion-in-depth information about where and when the target will arrive in a position suitable for capturing it. Important binocular clues to these 3D target properties include changing (dynamic) retinal disparity and interocular velocity differences, with tau (the inverse of the relative rate of retinal image expansion of incoming objects) an additional, monocularly available source of time-to-contact information. A powerful experimental paradigm for examining real-world interceptive behaviors involves one-handed ball catching, which has the advantage of combining quantification of the behavioral outcome (ie, the catching success rate) with kinematic analyses of the subject’s hand movements underlying successful versus failed catching attempts.

Work by Lenoir et al. (1999), later confirmed and extended by Mazyn et al. (2004), used this paradigm to compare the catching skills of young adult (aged 18–23 years) physical education students of similar ball-game experience, but with normal or reduced binocular stereovision. Affected participants (n = 9) in the latter study had stereoacuities of 400 arc secs or worse (the causes of which and whether they were also amblyopic was not reported). Yellow tennis balls were projected from a ProMatch machine over a distance of 8.4 m at speeds of 8.4, 11.6, or 14.6 m/sec (mean in-flight times of 1.0, 0.72, or 0.57 secs, respectively) towards the shoulder of each subject's preferred limb, the 3D kinematics of which were recorded by video and an infrared camera system that tracked markers placed on their catching arm and hand. Subjects attempted to catch 30 balls at each velocity in separate sessions using binocular vision or only their dominant eye.

Overall monocular catching success rates were identical (69%) for both subject groups and worse than their binocular performance, but normal participants had significantly higher mean success rates (92%) when using both eyes than did those with reduced stereoacuity (74%). In addition, the overall catching performance of both groups decreased with increasing ball speeds, a factor that contributed strongly to the poorer binocular skills of the stereodeficient catchers. At the lowest velocity with the ball in flight for 1 sec, binocular catching success was uniformly high (≥91%) in both groups and this dropped to 83% for control subjects when the highest velocity balls were in the air for around only half this time, but was almost at chance (54%) for the reduced stereoacuity subjects and no better than their monocular success rate (48%) at this fastest ball speed. Thus the binocular performance of the catchers with poor stereovision deteriorated more markedly as the task became increasingly time-constrained. These findings offer further support for the general idea that as time limits on movement execution become more stringent, the significance of monocular cues (eg, tau) normally reduces in favor of binocular information, and that such monocular cue sources are insufficient to compensate for loss of binocularity, even over the longer term in skilled practitioners (in this case, experienced sports players).

The kinematic analyses confirmed evidence from Lenoir et al. (1999) that the binocular catching failures had common causes across subjects. Specifically, missed catches were not associated with spatial errors in getting the hand into the correct position (ie, reaching), but with subsequent failures in timing the grasp, with the digits closing either too early or too late to successfully capture the ball. Evidence thus suggests that normal binocular stereovision is essential for accurate grasping of both moving and stationary objects.

Practice Effects in Stereo-Reduced Adults

In further support of this conclusion, Mazyn et al. (2007) have examined the effects of intensive binocular practice (>1,400 trials over a 2-week period) on their one-handed fast ball–catching task, in a control (n = 9) and reduced-stereo (n = 6) group of young adults with initially equally poor catching skills. Unlike the participants with normal binocularity, who showed a marked improvement (from ≈20% to 60%) in catching success in post-training and subsequent retention sessions, those with poor stereovision exhibited smaller (from ≈10% to 30%), and statistically insignificant practice effects.

Motivated in part by these findings, we have begun a post hoc exploration of whether stereodeficient adults benefited from practice on our simpler, reach-to-precision grasp tasks. The opportunity to do this arises from the fact that they repetitively directed movements towards and handled only a small set of stimuli (2 different objects, at 4 locations) on 144 trials over a period of ≈45 mins. They thus received both visual and non-visual feedback about the objects' properties; these potential learned perceptual associations resulting in improved performance (see Bingham et al., 2001; Keefe & Watt, 2009; Melmoth & Grant, 2006). Preliminary analyses of data obtained from the 10 non-amblyopic adults with no measurable stereopsis in Melmoth et al. (2009)

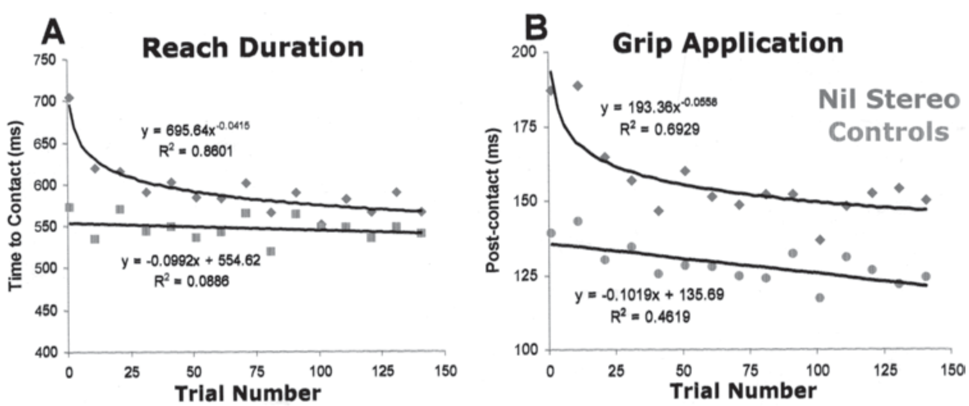

FIGURE 2 Rapid learning effects in non-amblyopic adults with nil (unmeasurable) stereo (diamonds) compared with normal (squares, circles) control subjects, as a function of (A) the reach duration, from movement onset to initial object contact, and (B) the grip application time, from initial object contact to lifting. Each symbol represents the average time, in milliseconds (ms), obtained over 8–10 consecutive trials for the entire experiment (6 separate blocks of 24 trials) in 10 participants of each subject group. Note 1: The average times are irrespective of the viewing (binocular, dominant eye, non-dominant eye) condition or object properties (size, location), which were presented in the same (randomized) 144 trial sequence to all participants. Note 2: All subjects were given several practice trials before the recording session (but with a different object and at different locations to those used in the experiment).

suggest that they do (Figure 2). Compared with pair-matched controls in this experiment whose performance was relatively stable over time, the reach duration and grip application times of the nil stereopsis subjects were extremely slow at first, suggesting that they were particularly disadvantaged when the task was novel. But they then showed rapid reductions in the timing of both movement components prior to stabilization, which were best fit by power (shown) and exponential functions, such that their visually guided reach durations did not differ from the controls by the end of the session, although their grip application times remained significantly longer. We are currently examining the extent to which these different effects applied to other movement parameters, such as planning (reaction) times, whether they occurred in each stereo-negative subject in the binocular condition, and if they generalized to those with residual (coarse) stereovision.

Walking

Maintenance of balance, posture, and gait while walking requires integration of vestibular signals relating to head position/motion, with proprioceptive information and vision of the environment, the importance of which is testified by the loss of equilibrium and mobility that normally occurs when the eyes are closed. Odenrick et al. (1984) compared posture and gait in 35 convergence "excess" strabismic children (aged 4.5–10.5 years), the majority (66%) of whom had no measurable stereopsis and/or mild-to-moderate amblyopia, with those of 100 controls matched for age and gender. Postural sway was measured on a force plate with the heels together and feet at 45° to each other in a dark room with a vertical rod subtending ≈3.5° of visual angle at 5 m provided as a fixation reference. Examinations were made with the eyes open or closed for 15 sec each, with a rest in between. Gait was measured from video recordings of subjects walking a straight 10 m path at different speeds (from "very slow" to "very fast"). Results of the postural tests were not particularly conclusive but, as a group, the strabismics took significantly shorter steps with briefer single limb support phases (while the other leg was swinging) than the normal children when walking slowly or at a normal comfortable pace, implying that they adopted a more careful strategy to maintain stability under these conditions. There was no correlation between the extent of this adaptation and their existing binocular function or strabismic deviation. Nonetheless, Odenrick et al. (1984) were among the first to explicitly suggest that visuomotor disturbances of the eye and limbs might be common consequences of abnormal binocular development.

In a more controlled and objective study, Buckley et al. (2010) examined the effect of abnormal binocularity on the control of gait, with the added challenge of obstacle-avoidance during the task. Participants were 10 adult strabismics and 6 anisometropes (aged 21–58 years) and 12 visually normal controls of similar dominant eye logMAR VA, age, gender, height, and weight. The majority of the strabismics and 1 anisometrope had no measurable stereoacuity; the others had reduced stereopsis with thresholds ranging from 85–600 arc secs. Roughly half of the two patient sub-types had mild-to-moderate amblyopia (logMAR 0.22–0.86 in the affected eye), with 1 strabismic showing a severe VA loss (logMAR 1.50). The task required subjects to walk 5 steps before negotiating an obstacle of different height (7, 15, 22 cm) placed in their path using binocular vision or with either eye occluded. Quantitative measures of the gait kinematics, such as the walking velocity in the approach to the obstacle, the penultimate stride length taken just before stepping over it, and the vertical distance by which the leading toe cleared the obstruction, were obtained from recording the 3D motion of markers placed on the subject's trunk and lower limbs. Because participants did not generally look directly at the obstacles while in the act of stepping over them, this experiment primarily assessed group, view and obstacle height-dependent differences in gait planning. To ensure that visual information was always employed for this purpose, the position of the obstacles in the walk path was varied (over a range of 30 cm) from trial to trial, with some no-obstacle ("catch") trials also included.

There were no significant differences in the overall performance of the subjects with or without amblyopia, but several effects of the viewing and/or obstacle conditions on the gait of the normal and stereodeficient groups. First, binocular walking velocities were faster, with larger penultimate step lengths in front of the obstacles and reduced vertical toe clearances when crossing them compared with dominant eye and, especially, to non-dominant eye viewing. These findings are mutually consistent with a more confident approach to the challenge when using both eyes and were present in both subject groups, if somewhat more marked in the normal adults. Second, toe clearance of the visually normal adults reduced with increasing obstacle height—indicative of energy conservation—but it *increased* in those with abnormal binocularity, suggesting that they added a further margin for error when planning their step-over to ensure that they avoided tripping. Most pertinently, the adaptive changes under habitual (binocular) viewing in both the penultimate step and toe clearance were significantly more marked in the stereo-reduced, suggesting that they may adopt this more careful strategy to obstacle-avoidance during everyday walking.

Driving

Evidence also suggests that stereo loss is associated with more prudent driving behavior. Tijtgat et al. (2008) investigated the contribution of stereopsis to the control of braking in front of a stationary target vehicle. Participants were 13 young adult (mean age 23 years) females with reduced (400 arc secs or worse) stereoacuity (the causes of which or presence of amblyopia were not reported) and 13 stereo-normal females of similar age and years of driving experience. Participants drove a go-cart fitted with a customized braking system at a constant speed of 11 km/h for 20 m to pass through a gate where the required vehicle approach velocity was verified. The stationary vehicle was positioned at the same distance from the gate, but at reducing distances (10, 7, or 4 m) beyond three subsequent gates that were passed. Subjects were instructed not to commence braking until a red tail-light fixed to the stationary vehicle was illuminated (when they passed one of these latter gates) and to stop behind it. Key findings were that the stereo-reduced participants tended to initiate braking earlier than the controls and to stop further away from the target, with the time of the peak deceleration in their final approach occurring significantly earlier in the braking maneuver, particularly over the two further stopping distances.

These findings might imply that stereo-reduced motorists are less prone to road traffic accidents. However, one notable epidemiological study reported a significantly higher incidence of crashes per year in taxi drivers with impaired binocularity than among normally sighted individuals of the same profession (Maag et al., 1997). Estimating braking distance is, of course, just one of many vision-dependent behaviors that contribute to safe driving; others include more dynamic and time-limited judgments that may be facilitated by stereopsis, such as the relative velocities of other vehicles and objects; changes in gap clearances between them; lane keeping; and constant updating of the road terrain via visual search saccades and other binocularly coordinated (smooth pursuit, vergence) eye movements.

Bauer et al. (2001) examined the effects of defective stereovision on such a real-world motoring task by requiring subjects to drive through a short, S-shaped slalom course between two lines of traffic cones. Ten manifest convergent (8–40 pD) strabismic amblyopes participated, all of whom had complete suppression in their deviating eye (negative Bagolini test) and, at best, gross Titmus fly positive (3000 arc secs) stereopsis, along with 10 controls matched for dominant eye VA, age (20–60 years), gender, yearly mileage, and driving experience. Subjects negotiated the slalom course on separate runs with both eyes open or with their non-dominant eye covered, and at similar times of day under equivalent weather conditions for matched subject pairs in each group, these paired data being used to evaluate overall group performance. The car operated in the tests was 2 m wide and was steered between cone lines separated by 2.75, 3, or 3.25 m (ie, with gap clearances of only 0.75, 1, or 1.25 m) randomized between runs, and at a constant speed of 40 km/h, maintained by an instructor in the front passenger seat. Touching or knocking over any one of the cones was scored as a failed run. These were more common in the stereo-defective group under each viewing condition, with both subject groups having more failures on dominant eye compared with binocular runs, although these latter effects of view were not statistically reliable, which Bauer et al. (2001) attributed to the small group sizes. Poor stereopsis, however, was associated with a significant (≈10-fold) increase in risk, compared with the controls, of colliding with the barriers when driving with both eyes open.

Reading

Reading involves a complex interplay between visual and oculomotor processes, whereby sequential saccadic eye movements are deployed to bring consecutive text elements onto the fovea in each eye, with brief intervening visual fixations used to extract the meaning of individual words and to permit the syntactical relationships between them to be comprehended. Many strabismics have abnormal eye movements characterized by saccade dysconjugacy (Kapoula et al., 1997) and marked fixation disparities (Kandel et al., 1980), so the oculomotor deficits in this amblyopia subtype might adversely affect their reading abilities. Two recent studies have compared the binocular and monocular reading performance of strabismic children (Stifter et al., 2005) or adults (Kanonidou et al., 2010) with those of normally sighted controls matched for sound eye logMAR VA, age, gender, and educational attainment. In both studies, a key dependent performance measure was the maximum reading speed (MRS), expressed as words per min (wpm).

Stifter et al. (2005) examined 20 children (aged 10–12 years) with unilateral microstrabismus (<5° convergent or divergent) and mild amblyopia (mean logMAR VA 0.19 in the affected eye). Participants read aloud sentences on Radner reading charts at 25 cm distance at a photopic luminance of 80–90 cd/m^2 as accurately and quickly as possible, without correcting any errors. The MRS was the optimal speed achieved across different print sizes. Developmentally normal children exhibited a small, but significant, binocular advantage in MRS (mean ≈200 wpm) over either eye alone (mean ≈190 wpm), whereas optimal binocular and dominant eye reading speeds were identical (173 wpm) in the microstrabismic group with marked impairment (mean ≈140 wpm) in their amblyopic eye. Direct comparisons also showed that the MRS of the microstrabismic children under the habitual (ie, both eyes open) viewing condition was significantly reduced (by ≈15%) compared with the controls, but with no significant between-group differences in sound/fixing versus dominant eye performance. There was, however, considerable variability in the binocular reading of the patient group, with almost half showing near-normal reading speeds (of >180 wpm). Further analyses revealed that the superior performance of this sub-group co-varied with the presence of central—rather than eccentric—fixation of the deviating eye and (consequently?) with better stereovision, but not with binocular logMAR (ie, letter) or reading (defined as the smallest critical print size that could be read at the optimal speed) acuities. Stifter et al. (2005) discussed the possible contributions of these visual and of potential oculomotor anomalies to the functional binocular reading impairment, but without drawing definitive conclusions.

The work of Kanonidou et al. (2010) sheds further light on this issue. They investigated the reading performance of 20 adults (aged 24–64 years) with manifest unilateral (convergent or divergent) strabismus and mild-to-moderate amblyopia (mean logMAR VA 0.33) in the affected eye, all of whom had central or total suppression in this eye and no measurable stereopsis. Subjects read, at their own pace sufficient to comprehend the text, 9 consecutive paragraphs from the fairy tale "Tom Thumb" presented (at >90% contrast) on a white (≈14 cd/m^2) projection screen, while their eye movements and fixations were recorded via a head-mounted infrared video eye-tracker. Participants read silently and with their head supported by a chin rest to prevent jaw movements that would compromise these recordings. At the fixed viewing distance (1.2 m), the standard print size corresponded to logMAR 0.76, at least 1.5 lines larger than the worst degree of amblyopia present. Comprehension of the full text was confirmed post-test by multiple choice questioning.

As with Stifter et al (2005), control subjects showed a small and significant binocular advantage in MRS (≈280 wpm) over their dominant and non-dominant eyes (both ≈265 wpm), an advantage that was lacking in the strabismic group. Indeed, reading speeds were significantly slower in these subjects compared with the normal adults under binocular viewing (187 wpm), amblyopic eye (156 wpm) and even the fixing/non-amblyopic eye (193 wpm) conditions. Kanonidou et al. (2010) speculated on the possible reasons for this latter discrepancy in relation to the Stifter et al. (2005) finding of equivalent dominant eye performance in microstrabismic and normal children. Likely candidates included the larger squint angles and vision losses in their adult subjects, as it is known that neither vision nor fixation stability are normal in the fixing eye of strabismic adults (Kandel et al., 1980) and that these deficits tend to be more marked with larger deviations and/or increasing depth of amblyopia in the affected eye. There were also important differences in task constraints; the children read short sentences as quickly as possible ignoring errors, whereas the adult's self-paced reading was intended to maximize comprehension (ie, accuracy) of much longer text passages.

Eye-tracking further showed that specific deficits in oculomotor control contributed to the reduced reading speeds of the adult strabismics under all 3 viewing conditions. Most consistently, the patient group made many (>1.5 times) more regressive (ie, leftward) saccades/line of text with significantly longer (≈20–30 ms) periods of fixation (under binocular and amblyopic eye viewing) than the control subjects. These findings imply that the strabismic subjects produced more saccades at the planning/programming stage that overshot the text elements required to obtain word meaning, so necessitating a corrective eye movement in the reverse direction, with slower visual processing at fixation underlying the extraction of meaning for comprehension. Partly for these reasons, Kanonidou et al. (2010) suggested that these problems were likely related to abnormalities of the strabismic visual system, such as suppression scotomas when viewing with both eyes and increased crowding effects when viewing monocularly with either eye (eg, Levi et al., 2007), rather than to a primary motor system deficit. Because their oculomotor problems were relatively subtle compared with their marked reductions in MRS, Kanonidou et al. (2010) further concluded that they represented just one of several causative factors of the functional reading impairments. These authors also raised the issue of whether objective analyses would reveal that reading deficits generalize to "pure" anisometropic amblyopes. We predict that they do, consistent with a meta-analysis of reading difficulties (Simons & Gassler, 1988) and evidence of saccadic dysfunction (delayed initiation, with increased variability and/or corrections) in adults with this sub-type of amblyopia (Niechwiej-Szwedo et al., 2010).

CONCLUSIONS: LIMITATIONS AND IMPLICATIONS

Our purpose in providing some of the clinical details of the affected participants in the studies reviewed here, along with quantitative data on their differences in performance versus matched controls, was partly to allow readers to draw their own conclusions about the significance of the visuomotor deficits described. A reasonable perspective is that the impairment exhibited on each of the tasks examined represents only a relatively minor disability. However, given that they were present on *every* task, then cumulatively, they could also be reasonably judged as likely to impact detrimentally on the habitual daily activities of individuals with amblyopia and abnormal binocularity. In support of this position, we would note that subjects with these disorders tend to behave cautiously and to employ adaptive measures that increase their margin for error, presumably because of uncertainty about their own abilities to perform the task, for example by attempting to trade off slower movements (Figure 1) for improved precision. Yet despite this, they still often fail to achieve normal levels of accuracy. Moreover, in real-world settings, this option is not always available because of the need to react quickly to sudden or expected events, and it is under these time-limited and novel (Figure 2) circumstances that their performance is particularly impaired. A clear implication of this is that amblyopia may be associated with an increased accident risk, an area which we believe deserves further large-scale epidemiological research.

It is important to acknowledge that the studies reviewed are subject to some common limitations. One is that binocularity was always assessed with routine clinical stereotests that measure static or position-in-depth stereopsis. Yet most of the real-world tasks discussed involved controlling the actions of moving body parts or in the presence of real or apparent object motion, for which knowledge of the participants' dynamic, stereo-motion thresholds may be of greater concern when seeking correlations between their visual deficits and motor behavior. While Cumming (1995) has shown that position- and motion-in-depth stereo-thresholds are closely related in normal adult observers, suggesting that they are mediated by output of the same cortical disparity detectors, there is evidence of greater preservation of motion-in-depth perception in strabismic amblyopes (Kitaoji & Toyama, 1987). A related concern, of which we have direct experience, is that subjects may be classed as having no measurable stereopsis because they fail the Titmus fly test (at 3000 arc secs), yet report having recently seen depth while watching a 3D movie. That is, their nil stereoacuity is falsely ascribed, as they possess binocular depth vision for low spatial/high temporal frequency disparity stimuli, which may be of some benefit for real-world task performance.

Other limitations relate to the notoriously variable causes of amblyopia and its binocular manifestations (eg, the presence of total, intermittent, partial, or no suppression in the affected eye) which, with some notable exceptions, are rarely reported or treated as independent factors in the task performance analyses. This is partly due to practical constraints on total participant numbers, but also to the tendency to recruit affected subjects opportunistically, resulting in relatively small and variable sub-groups of patients with strabismic and non-strabismic aetiologies (eg, Grant et al., 2007). Given that strabismus is generally associated with increased spatial mislocalization than anisometropia on perceptual tasks (Hess, 2002; Levi & Klein, 1985), one might reasonably expect the visuomotor abilities of strabismic amblyopes to be more affected than that of anisometropes with equivalent deficits in binocular stereovision. However, only one of the studies reviewed, by Webber et al. (2008), had sufficient power to provide persuasive evidence that this may indeed be the case.

Nonetheless, a highly consistent finding is that children and adults with no clinically measurable stereoacuity exhibit the least accomplished real-world visuomotor skills. A clear implication of this, which has been emphasized by various authors (eg, Melmoth et al., 2009; O'Connor et al., 2010), is the need to adopt amblyopia treatment strategies for restoring or maintaining the highest levels of stereoacuity possible, as even residual binocularity appears sufficient to confer functional benefits on some everyday tasks.

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