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Fixational ocular motor control is plastic despite visual deprivation

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Abstract

The aim of this study was to assess the plasticity of human voluntary fixational eye movement control in relation to visual experience/chronic visual deprivation. Twelve blind adults participated (self-reported vision ≤ light perception in each eye; age range = 23–56 years; visual experience range = 0–28 years; blindness duration range = 6–55 years). Infrared-based recordings of horizontal eye movements were made before, during, and immediately after three 30-s periods of auditory ocular motor feedback, while participants were instructed to look straight ahead and keep their eyes as steady as possible. Percent change in horizontal displacement of the eye during and after feedback was compared with the no-feedback baseline. Eleven of the 12 individuals demonstrated feedback-mediated increase in eye stability, which improved as a function of visual experience. Improved eye stability was inversely related to duration of blindness. Clearly, blind adults can use nonvisual external feedback to stabilize gaze. Thus, the fixational subsystem can exhibit improved voluntary control despite chronic visual deprivation. Possible cortical and subcortical mechanisms are discussed.

Keywords: Blindness, Feedback, Fixation, Oculomotor, Plasticity

Introduction

Visual deprivation and ocular motor control

This research investigated the plasticity of fixational ocular motor control and its relationship to visual experience. Previous work quantified how, without external feedback, adults' voluntary ocular motor control depends most strongly on length of childhood visual experience, secondarily on recency of adventitious blindness, and least importantly on immediate visual input (Hall et al., 2000*a*). In that study, blind and normally sighted adults were asked to "look straight ahead" in total darkness. Eye stability increased with duration of visual experience, leveling off when blindness onset had occurred well into adolescence. Nystagmus waveforms unique to blindness also were identified which resemble patterns that can impair vision (including latent manifest-latent nystagmus; Hall et al., 2000*b*). Evidence from these and other studies implicates abnormal functioning of central ocular motor areas, possibly attributable to (visual deprivation-based) degeneration and/or failure to develop (Leigh & Zee, 1980; Sherman & Keller, 1986; Kompf & Piper, 1987; Leigh et al., 1989).

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Auditory ocular motor feedback

Auditory ocular motor feedback (AOM feedback), in which individuals "hear their eyes move," refers to pitch-varied tonal feedback related to change in eye position (see, e.g. Hung et al., 1988; for a review see Ciuffreda et al., 2002). This technique has been used experimentally in individuals with poor central vision to increase reading rate (Hall & Ciuffreda, 2001), maintain relatively accurate vergence (Shelhamer et al., 1994), and, in the absence of specific visual cues, maintain fixation (Smith, 1964; Hung et al., 1988). Clinically, AOM feedback has been used to limit or reduce the deleterious visual effects of eye movement abnormalities, including nystagmus and abnormal saccadic intrusions (see, e.g. Abadi et al., 1981; Ciuffreda et al., 1982; Ciuffreda & Goldrich, 1983; Abplanalp & Bedell, 1987; Ciuffreda et al., 2002). It is thought that AOM feedback improves intentional control by drawing attention to and/or heightening awareness of one's eye movements (Fayos & Ciuffreda, 1998), perhaps bringing higher-order brain centers to bear on the task (Hall & Ciuffreda, 2001).

In designing the present study, it was hypothesized that given external nonvisual information about change in eye position, blind adults can voluntarily increase fixational ocular motor control, as measured by a decrease in eye displacement. This cross-modal approach uses sound to drive the ocular motor areas of the deprived visual system. It provides a direct noninvasive measure of behavioral plasticity; furthermore, it precludes possible confounds

Table 1. *Clinical data*[a]

Participant code	Visual experience: Years vision	Visual experience: Years blind	Clinical history
CSM1	0	55	ROP OU
CKG1	3	48	Congenital glaucoma OU; corneal transplant OD (unsuccessful)
CJW1	3	53	ROP OU
CRH1	6	30	Detached retina OU (familial exudative vitreo retinopathy)
CRW1	11	31	Congenital glaucoma OU
CPJ1	12	35	Congenital glaucoma OU
CPS1	14	35	ROP OU; cataracts age 14 years OU (cataract extracted & eye muscles "tightened" age 19 years OS)
XRD1	17	6	Detached retina OU (age 6 years OD, 17 years OS); congenital cataract, OU (extracted age 6 months OD, 1 year OS)
CAC1	18	26	Retinitis pigmentosa OU (10 deg visual fields until age 18 years)
XEH1	19	17	Coloboma (spherical & retinal) OU; microophthalmia, OS; cataract age 19 years, OD
AFB1	21	7	Retinitis pigmentosa OU
XDS2	28	24	Congenital glaucoma OU (enucleation age 11 years OD; detached retina age 26 years, cataract, OS).

[a]ROP = Retinopathy of prematurity, OD = right eye, OS = left eye, and OU = both eyes.

attributable to visual input. The resulting eye movement recordings also are used to gauge the functioning of visually deprived ocular motor brain areas.

Methods

Participants

Data were gathered from 12 blind adults (self-reported vision ≤ light perception in each eye; age range = 23–56 years; visual experience range = 0–28 years; blindness duration range = 6–55 years; see Table 1). The experiments had received institutional review board approval, were in accordance with the tenets of the Declaration of Helsinki, and were undertaken with the understanding and signed consent of each participant.

Apparatus

Infrared-based recordings of horizontal eye movements were made using a modified Ober-2 Research Model Eye Movement System (Permobil, Sundsvall, Sweden) (linearity: ≥ ±10 deg; resolution: 0.25 deg; bandwidth: DC to 120 Hz). The eye movements were recorded on a three-channel strip chart recorder (bandwidth: DC to 50 Hz). The recorded eye movement signal was transmitted simultaneously to a custom-designed audio oscillator to produce an audio signal that changed continuously and systematically with variation in horizontal eye position. This signal in turn was fed to a speaker positioned behind the observer (see Fig. 1); specifically, the tone increased in pitch as the eye moved to the right, and decreased when the eye moved to the left.

Procedures

Each participant was seated in an ophthalmic chair, and the infrared goggles were placed to fit snugly over the eyes. A forehead/chin rest with Velcro straps was used to ensure head stability. The goggle-based infrared sensors were adjusted laterally and vertically for optimal placement in front of whichever eye had the least motor deviation and/or corneal scarring.

Gain control procedure

Calibration in the classical sense was not possible (because all of the participants were blind). To monitor consistency of response size, and hence eye displacement, each participant was asked to look left and right repeatedly, making equivalently sized saccades as per the experimenters' instruction. This procedure was carried out several times per session. Recordings showed remarkably consistently sized eye displacements in the evaluated lateral range. Fig. 2 contains an example from one individual (representative of the performance of all 12 participants). These data preclude the possibility that the experimental results could represent artifact (e.g., saturation) or substantial variation in gain control during experimental recording.

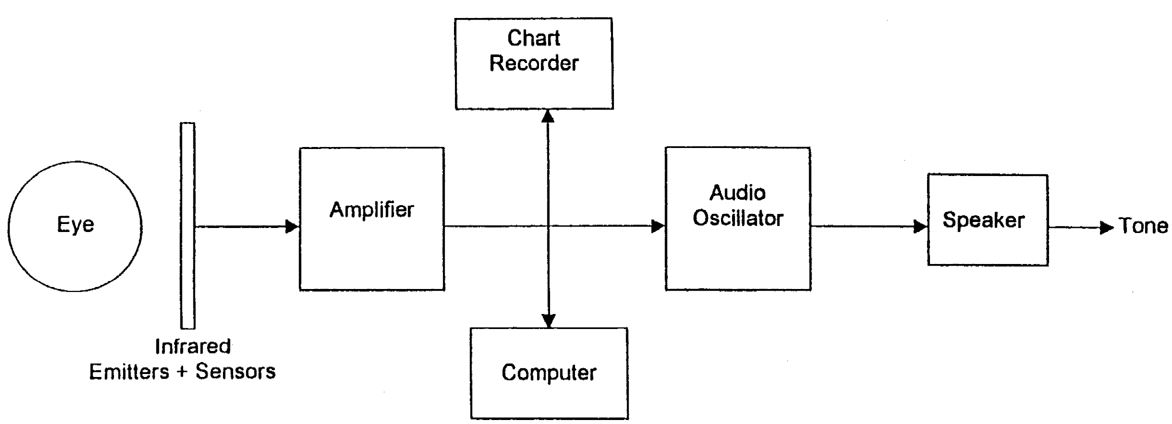

Fig. 1. Schematic representation of the auditory ocular motor feedback system.

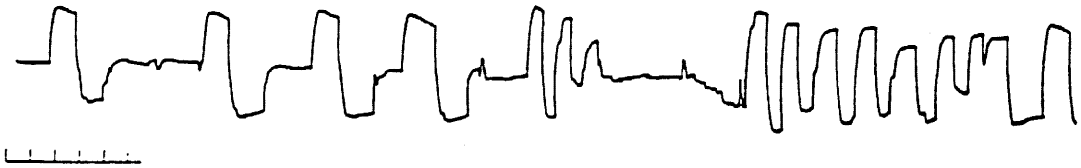

Fig. 2. An example of eye movement recordings in which the participant was asked to look left and right repeatedly, while attempting to make equivalently sized saccades; results show consistent eye movement response sizes over the same lateral range. Tick marks represent 1-s intervals. Upward deflections in record indicate leftward, and downward deflections indicate rightward eye movements.

Experimental procedure

An ABA experimental design was used.

A: Prior to feedback, participants were asked (3 times, 30 s each) to look straight ahead and keep their eyes as steady as possible.

B: Tonal feedback was begun; it was explained that the ocular motor feedback relative pitch (and its changes) depended on lateral gaze position and variability. Participants were asked (3 times, 30 s each) to look straight ahead and use the "eye movement sounds" to keep their eyes as steady as possible.

A: Feedback was terminated, and (immediately) the eye movement instruction was repeated three times (30 s each).

Analysis procedures

All 12 sets of eye movement recordings were evaluated by one of the authors (KJC, an experienced ocular motor optometrist and researcher) who was unaware of the visual experience/blindness duration of the participants. The entire data record of each participant was examined first. That is, all three 30-s intervals under each condition from each of the 12 data sets were inspected visually.

Each participant's most representative 30-s interval within each experimental condition was selected for precise measurement; the selections were made also such that a minimum of artifact (e.g. blinks) was included. The selection process yielded three segments of record (one before, one during, and one after AOM feedback) per participant. In each of these 30-s intervals, eye stability within the central approximately 27 s was quantified; elimination of the initial and final seconds was done to exclude possible initiation and/or fatigue effects. Figs. 3 and 4 show the selected segments of eye movement record before, during, and immediately after AOM feedback, from all 12 individuals (panels A-L).

Eye stability was assessed by quantifying the total displacement of the eye (in mm) in each 27-s segment of record, including drifts and saccades but not including blinks.

The percent change in this variable during and after feedback (compared to the no-feedback baseline) was calculated.

Statistical evaluation: The Pearson product-moment correlation coefficient, r, was calculated to analyze trends. All correlations were further evaluated using two-tailed significance tests.

Results

Table 2 lists percent change (compared to no-feedback baseline) in eye displacement during and after feedback, for all 12 participants.

Change in eye stability during feedback

Eight of the 12 participants showed a decrease in eye displacement during feedback (mean = 35%, range = 10–83%). This improvement in eye stability was significantly and positively correlated with visual experience ($r = 0.83$, $P = 0.01$, two-tailed, $N = 8$). Fig. 5 depicts the percent decrease in eye displacement during feedback as a function of visual experience; the data points show a positive trend, indicating that the longer the visual experience, the greater the improvement in eye stability during auditory ocular motor feedback (slope = 2.51). Improvement in this variable during feedback furthermore was inversely related to increase in blindness duration. As shown in Fig. 6, percent decrease in eye displacement during feedback was negatively correlated with blindness duration in this subgroup ($r = -0.52$, $P = 0.19$, two-tailed, slope = -0.87, $N = 8$). One of the 12 participants showed no change in eye displacement; three increased (mean = 32%, range = 4–56%).

Change in eye stability after feedback

Eleven of the 12 participants showed a decrease in eye displacement postfeedback (mean = 34%, range = 5–75%). This trend was characterized by a modest positive correlation in relation to visual experience (see Fig. 7, $r = 0.41$, $P = 0.21$, slope = 1.04, $N = 11$). Blindness duration was weakly negatively correlated with percent decrease in eye displacement following feedback ($r = -0.19$, $P = 0.57$, data not shown). One individual showed a 17% increase in this variable.

Comparison of change in eye stability

In some cases the after-feedback percent change was greater than the during-feedback percent change, and in one case was equal to the change during feedback (see Table 2). In four participants, the percent change during feedback exceeded that after feedback.

Discussion

These results show that despite childhood blindness, blind adults can use external nonvisual information about change in eye position to improve eye stability, even when given only an extremely brief period of auditory ocular motor feedback (i.e. 1.5 min total). Thus, despite extremely abnormal visual experience, the fixational subsystem can function to improve ocular stability under voluntary control.

It is reasonable that the longer the visual experience, the greater the improvement in eye stability, both during and after AOM feedback (particularly in light of the previously identified positive correlation between visual experience and eye stability in blind adults given no feedback, see Introduction). Similarly reasonable is the inverse relationship that emerged between the blindness duration and feedback-mediated improvement in eye stability. The identified patterns should be considered modest, however, in the context of the larger data set (see also Future Directions, below).

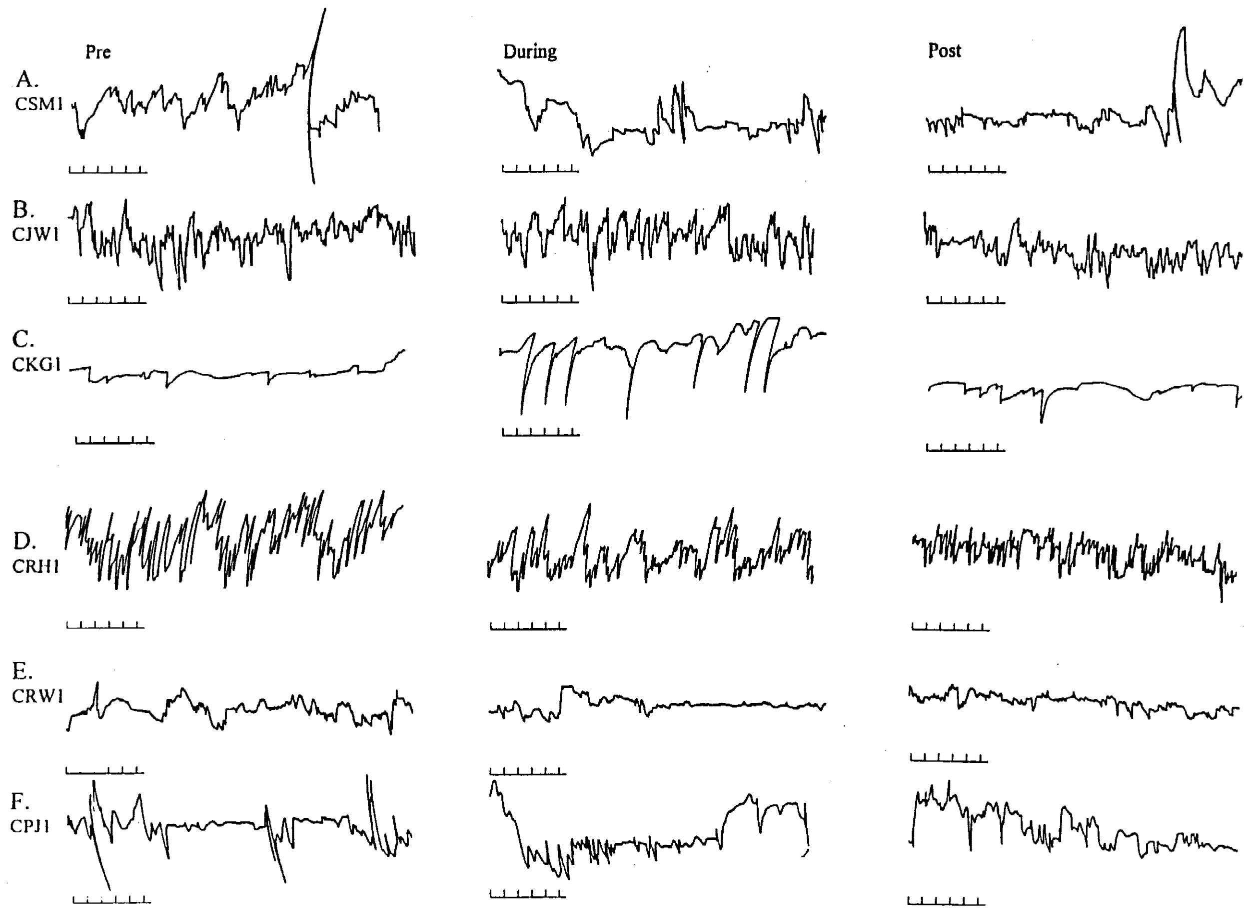

Fig. 3. Eye movement recordings: Panels A–F present eye movement recordings from six of the 12 individuals before, during, and after tonal feedback. In each instance, the individual was instructed to "Look straight ahead and try to keep your eyes as steady as possible." Tick marks represent 1-s intervals. Upward deflections in record indicate leftward, and downward deflections indicate rightward eye movements.

Neural mechanisms

The neural basis of the increased stability depicted in Figs. 5 and 6, during feedback, and Fig. 7, after feedback, could be cortical and/or subcortical. The latter, simpler, explanation is that auditory afferent activity influenced ocular motor control regions in the superior colliculus, which in turn affected pre-motor elements in lower structures (e.g. cerebellar areas, the nucleus prepositus hypoglossi, and the medial vestibular nucleus; see also Leigh & Zee, 1999). Related evidence suggests that facilitatory convergence of visual and auditory afferent activity onto single neurons in the human superior colliculus may combine to produce saccadic gaze shifts (Hughes et al., 1998).

Alternatively, the stability improvements may have occurred by cortical auditory processing and fixation control regions interacting, in top–down fashion, to influence mid–brain and lower ocular motor control areas. The intentional nature of the task may support a cortical explanation. This would be consistent with evidence, for example, that programming of volitional saccades involves the frontal eye fields, the supplementary eye fields, and related structures (see, e.g. Pierrot-Deseilligny et al., 1995; Leigh & Zee, 1999). It should be noted that evidence of saccadic control mechanisms is cited here simply by way of example, in the absence of much comparably relevant fixation literature.

Plasticity

The results of this study support the idea that voluntary ocular motor control was not simply untapped in blind respondents. Rather, in the absence of visual guidance about eye position, the system used the available cross-modal input, responding dynamically to generate volitional control where little or none existed previously.

The feedback tone presumably allowed a previously inaccessible pathway, leading from auditory sensory processing to ocular motor control areas, to be activated to improve fixational stability. Were it possible to deliver meaningful verbal feedback as quickly as it is to present pitch-varying tonal feedback, similar results might have been produced using instruction alone; the immediacy as well as the salience of the tonal feedback may account in part for this hypothetical discrepancy.

The effects shown were obtained in less than 2 min. The minimum duration of auditory ocular motor feedback to activate cortical or lower brain areas to increase eye stability remains untested. However, the second author (KJC) has found similarly rapid results in some clinic patients with congenital nystagmus. Plasticity elsewhere in the human visual system, furthermore, has been demonstrated to take place even faster, in less than 1 s (Kapadia et al., 1994), although the task did not involve ocular

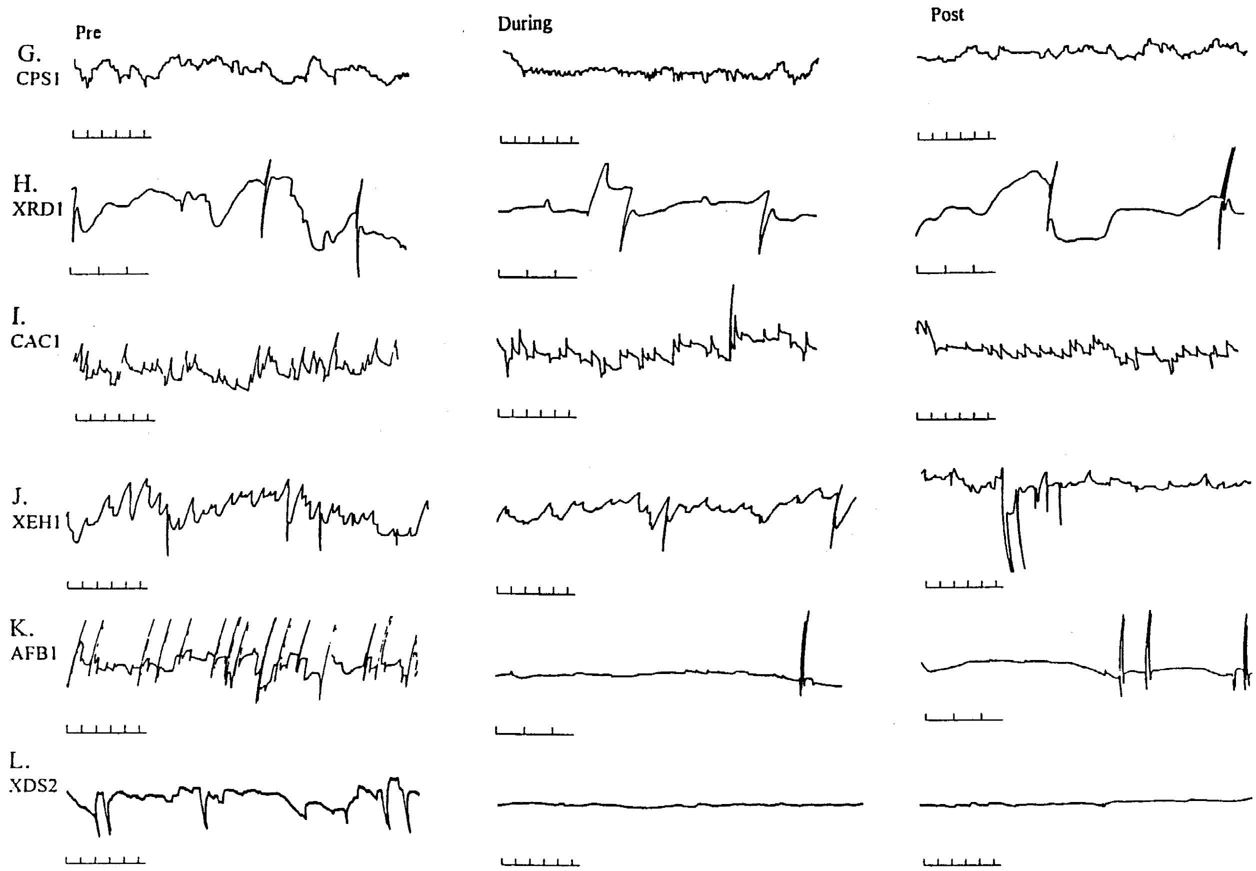

Fig. 4. Eye movement recordings: Panels G–L present eye movement recordings from the remaining six individuals before, during, and after tonal feedback. In each instance, the individual was instructed to "Look straight ahead and try to keep your eyes as steady as possible." Tick marks represent 1-s intervals. Upward deflections in record indicate leftward and downward deflections indicate rightward eye movements.

movement, which imposes inherent delays on the system (see, e.g. Ciuffreda & Tannen, 1995).

The feedback-mediated acquisition/improvement in fixational control may be attributable in part to a heightening of awareness. Alerting blind adults to eye position may have acted either to establish or to reestablish ocular proprioception in these individuals (who, depending upon age of blindness onset, may report inability to apprehend their own eye position; Hall et al., 2000*a*). Because the participants were blind, furthermore, there was no conflict between visual and auditory feedback. This precluded the possible attentional confound of a visual distractor in which, in a

Table 2. *Percent change in eye displacement amplitude during and after AOM feedback*[a]

Participant code	During feedback	After feedback
CSM1	−14	−21
CJW1	4	−19
CKG1	36	−45
CRH1	−13	−33
CRW1	−29	−43
CPJ1	56	17
CPS1	−10	−20
XRD1	−30	−5
CAC1	0	−12
XEH1	−33	−28
AFB1	−69	−69
XDS2	−83	−75

[a]Negative values represent improvement in eye stability; positive values indicate decrease in eye stability.

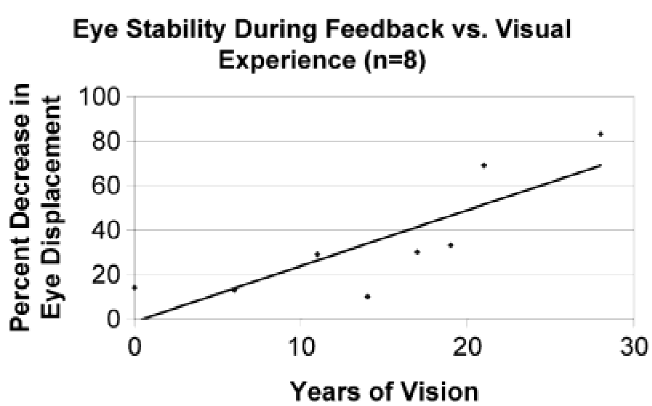

Fig. 5. Percent decrease in eye displacement during AOM feedback as a function of years of visual experience; slope = 2.51, $r = 0.83$, $P = 0.01$, two-tailed, $N = 8$.

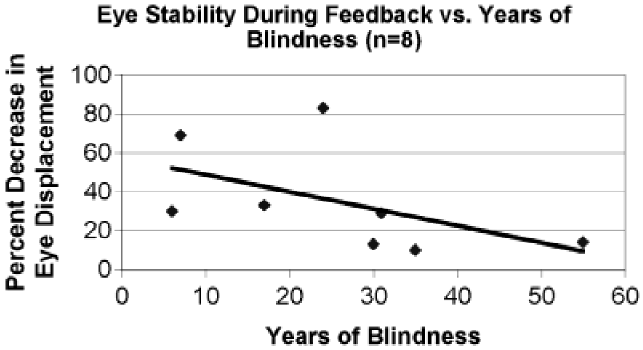

Fig. 6. Percent decrease in eye displacement during AOM feedback as a function of years of blindness; slope $= -0.87$, $r = -0.52$, $P = 0.19$, two-tailed, $N = 8$.

previous study, eye stability decreased slightly during attempts by normally sighted individuals to fixate, with reduced central visual input, using auditory ocular motor feedback (Smith, 1964). The effect of successfully practicing the task during feedback may account for those instances in which improvement was greatest after feedback. Fatigue is likely responsible for the instances in which fixational stability decreased during or after feedback as compared to baseline. Both practice and fatigue are variable, and, in particular, fatigue is reported much more commonly in blind than in sighted adults performing the same ocular motor tasks (unpublished data of ECH).

Future directions

Eye stability typically did not approach that of normally sighted individuals fixating in the dark (see, e.g. Matin et al., 1970; Skavenski & Steinman, 1970; Hung et al., 1988). It will be interesting to attempt longer and/or repeated training periods to investigate this discrepancy systematically, as well as to assess the permanence of the training effect and the minimum training time required to obtain lasting results.

Future research also will use behavioral and neurophysiological techniques to assess the plasticity of saccadic, pursuit, and vergence control in relation to visual experience/chronic visual deprivation. The anomalies portrayed by the present recordings add to previous evidence of abnormal functioning of central ocular motor areas in blindness, which has included direct neurophysiological assessment (Hall et al., 1999; Hall et al., 2000*c*), and the behavioral data already noted.

The ability to increase eye stability using auditory feedback raises exciting clinical as well as basic scientific possibilities. First, it may be useful in improving feedback protocols (already in use in some large clinics) for treating individuals with vision loss arising from nystagmus. Second, it suggests that if attention can be directed appropriately, then cross-modal cooperation of auditory and ocular motor brain areas can be elicited to acquire new control over abnormal eye movement.

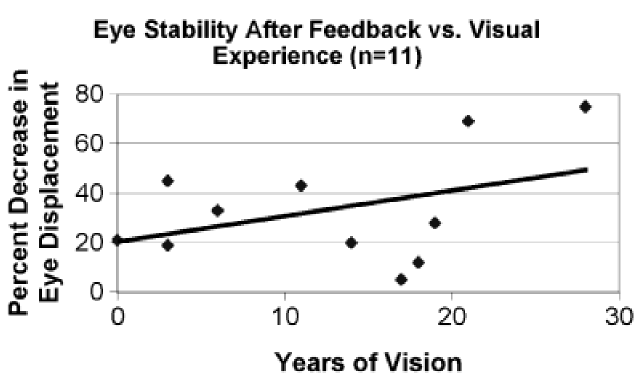

Fig. 7. Percent decrease in eye displacement after AOM feedback as a function of years of visual experience; slope $= 1.04$, $r = 0.41$, $P = 0.21$, $N = 11$).

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