Control of unsteady, eccentric fixation in amblyopic eyes by auditory feedback of eye position

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A technique for providing amblyopes with auditory feedback signals of eye position errors is described. With auditory cues, 12 adult eccentrically fixing amblyopes with strabismus and/or anisometropia have been able to maintain steady and foveal fixation with the amblyopic eye. The changes observed in fixation patterns with auditory feedback were both quantitative and qualitative; with such feedback, amblyopes often exhibited sequences of normal-appearing fixation. Some of our subjects have been successful in maintaining steady foveal fixation for short periods of time after feedback is turned off, apparently using visual error signals. For two subjects, feedback also promoted major improvements in smooth tracking performance. We conclude that the use of auditory feedback of eye position has significant value for basic studies of the mechanisms underlying amblyopia and potentially for the clinical treatment of this condition.

Key words: amblyopia, auditory feedback, eccentric fixation, eye movements, strabismus, anisometropia, foveal fixation

Monocular fixation of anisometropic and squinting amblyopic eyes is characterized by marked unsteadiness1-5 and, in most squinters, by the use of an off-foveal locus.2-7 Large drifts,5-7 increased drift velocity,5-9 and the intrusion of relatively large saccades3-9 contribute to the fixational unsteadiness of amblyopic eyes. Their drift is generally asymmetric2,5,9 (i.e., directionally biased), and saccades are both error-correcting (i.e., toward the fixation locus) and error-producing (away from fixation).5 The amplitude of the fixational unsteadiness of amblyopic eyes tends to increase with the depth of amblyopia.5

Recently, visual acuity was measured across the horizontal meridian in several amblyopic eyes while these observers used auditory feedback of their eye position to eliminate fixational eccentricity and reduce unsteadiness to normal or near normal limits.12-14 Acuity at the fovea of the amblyopic eye was at least equal, and in most cases superior, to the acuity at the retinal locus used for eccentric fixation. We report here on the influence of this auditory feedback technique on the fixation pattern of eccentrically fixating, functionally amblyopic eyes.

Auditory and visual feedback have recently been used in a number of laboratories and clinics in attempts to permit experimental subjects or patients to control their accommodation,15-17 binocular alignment,18-20 or cyclorotary eye position.21 Of particular relevance to the present report is the recent report of Schor et al.19 that amblyopes given auditory information about when they made saccades could reduce the number of sac-
cades made during monocular fixation with the amblyopic eye. Ciuffreda et al. have reported a similar reduction of fixational saccades by amblyopes simply by changing their instructions. Smith showed that normal subjects could use auditory feedback of eye position to improve fixation when the visual fixation target was poorly defined or when it was absent (i.e., in darkness).

Our paper demonstrates that (1) within a relatively short period of time adult amblyopes learn to use auditory feedback of horizontal eye position to control fixational unsteadiness and eccentricity of the affected eye, (2) with training, auditory feedback reduces the amplitude of both drift and saccadic components of fixational unsteadiness with an additional selective reduction in the frequency of intrusive error-producing saccades, and (3) amblyopes trained in the use of auditory feedback show the ability to use visual information to hold steady foveal fixation for short periods of time after the auditory feedback is discontinued. Improved steadiness and centricity of monocular fixation with the amblyopic eye are regarded clinically as requirements for improved acuity.

Methods

The instrumentation and methods reported here are essentially those used to obtain acuity measures across the retina of eccentrically fixating amblyopic eyes under conditions of steady foveal fixation. Horizontal eye position was detected with an infrared, limbal-reflecting, eye movement monitor (Gulf Western Industries). The device was mounted directly onto the subject's spectacles or onto a blank spectacle frame. Sensitivity was 5 min arc or less. The use of a bite bar minimized confounding head movements. Eye position and (by differentiation) velocity signals were registered on a strip chart recorder and monitored by the experimenter during testing. Eye position signals were also used to drive an audio-oscillator, the output of which was fed to the subject's left and right ears through stereo head-phones. Changes in eye position which extended beyond a calibrated deadband region, the width of which was controlled by the experimenter, activated the feedback mechanism. When the subject's fovea moved outside of the deadband to either the right or the left, a tone was provided to the corresponding ear. The feedback signals were frequency modulated so that the pitch of the tone signal increased with the magnitude of the eye position error. Thus the subject's tone was more highly pitched the farther his eye moved from the central deadband. When the fovea was inside the deadband, the subject heard no sound or heard a clicking sound when the fovea was precisely centered within the deadband.

The deadband was centered at the fovea by having the subject position his Maxwell's spot between two triangular fixation targets located straight ahead. Maxwell's spot, an entoptic projection of the distribution of the macular pigment, was made visible in our experiments by alternately illuminating the viewing screen with purple and neutral lights. To calibrate the gain of the feedback system, the subject positioned Maxwell's spot between additional pairs of targets located 3° to the right and left of the central fixation target. After calibration was completed, the Maxwell's spot-inducing lights were turned off. Thereafter, auditory feedback signals provided the subject with information as to the direction and magnitude of horizontal position errors between the fovea (Maxwell's spot) and the central fixation target. Subjects were instructed to respond to auditory cues as quickly as possible and to attempt to keep the sound off in both ears.

During training, subjects viewed the concave surface of a large, white cylindrical screen from a distance of 2.2 m. Three pairs of fixation targets were continuously visible on the screen. After the initial periods of training, the subjects performed acuity and tracking tasks with targets presented on this screen and set contrast thresholds for grating targets displayed on an oscilloscope. Feedback signals were provided to maintain steady foveal fixation during these tasks.

For initial training, the deadband was set fairly wide (±40 min arc). As each observer gained proficiency in using the auditory signals, the deadband was progressively narrowed and was finally set at ±15 or 20 min arc. Training or ex-
Table I. Relevant clinical information for the 12 functional amblyopes with eccentric fixation who used auditory feedback to control fixation of the amblyopic eye

<table>
<thead>
<tr>
<th>Subject</th>
<th>Acuity</th>
<th>Monocular fixation (Δ)</th>
<th>Ametropia</th>
<th>Angle of deviation (Δ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. G.</td>
<td>R 20/70</td>
<td>1 Temporal</td>
<td>+0.25 DS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L 20/15</td>
<td></td>
<td>-1.75 - 0.50 × 5</td>
<td>2 Esotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/15</td>
<td></td>
<td>-8.25 DS</td>
<td></td>
</tr>
<tr>
<td>P. P.</td>
<td>L 20/109</td>
<td>3 Nasal</td>
<td>-7.25 DS</td>
<td>11 Exotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/20</td>
<td></td>
<td>+5.50 - 0.50 × 165</td>
<td>11 Hypertropia</td>
</tr>
<tr>
<td>L. S.</td>
<td>L 20/50</td>
<td>2 Temporal</td>
<td>+4.75 - 1.00 × 15</td>
<td>17 Exotropia</td>
</tr>
<tr>
<td></td>
<td>R 20/160</td>
<td>6 Temporal</td>
<td>+0.75 - 3.00 × 5</td>
<td></td>
</tr>
<tr>
<td>M. B.</td>
<td>L 20/20</td>
<td></td>
<td>-1.50 - 3.00 × 170</td>
<td>12 Exotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/13</td>
<td></td>
<td>-1.00 DS</td>
<td>3 Hypertropia</td>
</tr>
<tr>
<td>S. T.</td>
<td>L 20/90</td>
<td>6 Nasal</td>
<td>-0.62 - 0.50 × 173</td>
<td>14 Exotropia*</td>
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<tr>
<td></td>
<td>R 20/12</td>
<td></td>
<td>+2.00 DS</td>
<td></td>
</tr>
<tr>
<td>C. D.</td>
<td>L 20/277</td>
<td>2 Nasal</td>
<td>+7.75 - 0.75 × 85</td>
<td>16 Exotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/20</td>
<td></td>
<td>+0.75 - 1.25 × 131</td>
<td></td>
</tr>
<tr>
<td>L. M.</td>
<td>L 20/40</td>
<td>1 Nasal, 0.5 superior</td>
<td>+1.00 - 0.75 × 150</td>
<td>5 Exotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/15</td>
<td></td>
<td>-1.00 DS</td>
<td></td>
</tr>
<tr>
<td>J. F.</td>
<td>L 20/180</td>
<td>2 Temporal, 0.8 inferior</td>
<td>+1.75 DS</td>
<td>20 Esotropia</td>
</tr>
<tr>
<td></td>
<td>R 20/40</td>
<td>2 Nasal, 1.8 inferior</td>
<td>-1.00 - 0.25 × 20</td>
<td></td>
</tr>
<tr>
<td>D. C.</td>
<td>L 20/20</td>
<td></td>
<td>-3.25 - 0.50 × 90</td>
<td>12 Exotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/12</td>
<td></td>
<td>+0.25 DS</td>
<td>2 Hypertropia</td>
</tr>
<tr>
<td>P. F.</td>
<td>L 20/87</td>
<td>2 Nasal</td>
<td>+3.25 - 0.75 × 15</td>
<td>2 Esophoria</td>
</tr>
<tr>
<td></td>
<td>R 20/20</td>
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<td>-0.50 - 0.50 × 79</td>
<td></td>
</tr>
<tr>
<td>D. W.</td>
<td>L 20/250</td>
<td>9 Nasal, 6 superior</td>
<td>+1.25 - 0.50 × 135</td>
<td>23 Esotropia*</td>
</tr>
<tr>
<td></td>
<td>R 20/20</td>
<td></td>
<td>-2.25</td>
<td>10 Hypertropia</td>
</tr>
<tr>
<td>J. K.</td>
<td>L 20/70</td>
<td>3 Nasal, 1 superior</td>
<td>-1.50 - 0.75 × 165</td>
<td>8 Esotropia*</td>
</tr>
</tbody>
</table>

*Anomalous retinal correspondence.

Experimental sessions were scheduled for 1 to 2 hr once or twice per week. On this schedule, the progress made during one training session was carried over to the next.

Results

Eye position–auditory feedback training has been provided to 12 adult amblyopes over the past 3 years. Our sample included six exotropes, four exotropes, and two non-squinting anisometropes. Visual acuities of the amblyopic eyes ranged from 20/40 to 20/250. Relevant data for these subjects are presented in Table 1.

After 2 to 7 hr practice (median about 3.5 hr), all subjects were able to maintain foveal fixation within 20 min arc of the target with their amblyopic eye for several seconds at a time using auditory feedback.* By foveal

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*In general, fixation with the fellow nonamblyopic eye was foveal and maintained within 20 min arc of the target at the initial visit without auditory feedback. We did not attempt to improve the accuracy of the fixation.
Fig. 1. Records of horizontal eye position show the fixation behavior of six amblyopic eyes without (left of arrows) and with (right of arrows) auditory feedback of eye position. Periods of steady foveal fixation (within ±20 min arc) are evident in each record when feedback is provided. One such period is shown for each subject by a horizontal line under the trace. Vertical calibration bars to the left of each trace are 3°. Associated time scales (1 sec divisions) are shown above the top two records and above the bottom four. In this and all subsequent figures, upward deflections denote eye movements to the left.

fixation we mean that the subject aimed the fovea (Maxwell’s spot) at a target and attended to that target. Representative records of several amblyopes’ fixation patterns obtained with and without auditory feedback are shown in Fig. 1. Most noticeable during the periods of steady fixation with auditory feedback was the relative absence of large-amplitude saccades that normally occur during fixation by amblyopic eyes (e.g., Fig. 1,
Amblyopic-eye fixation control by auditory feedback

Fig. 2. The eye position records for two amblyopic eyes show slow drifts that corrected eye position errors which were signalled by auditory feedback. The “deadband” of the auditory feedback system is indicated for each eye by the flanking cross-hatched areas. Associated time scales, in seconds, are above each record. The vertical calibration bars are 3°.

c). Also apparent during the steady-fixation periods with feedback are the reduced amplitude and velocity of eye drifts compared to the no-feedback condition (e.g., Fig. 1, b and e).

Steady fixation was not generally obtained during the initial periods of feedback when the central deadband was set at about ±40 min arc. During initial training, subjects attempted to reduce eye position errors signalled by auditory feedback, by making corrective saccades that tended to be too large, resulting in the eye “jumping” from one side of the deadband to the other. With further practice, the subjects seemed to adjust their corrective saccades according to the pitch of the auditory signals and to re-aim the eye accurately within the center of the deadband. Most subjects experienced occasional difficulty maintaining steady fixation even after considerable practice with feedback. On these occasions, large corrective saccades were evident with the eye jumping back and forth across the deadband—as occurred initially in the training.

In addition to saccades to return the amblyopic eye to the deadband, many of our subjects used slow eye movements. An example of the correction of eye position error with slow control is shown for Subject S. T. in Fig. 2. Here the direction of eye drift reversed from right to left after a feedback tone signaled a position error to the right. A short time later, eye drift reversed direction from left to right to correct a position error to the left. (During fixation without feedback, S. T.’s fixation showed a strong rightward drift bias.) At other times S. T. used saccades to re-aim the eye to the deadband. Another subject, M. B., showed some leftward drifts that corrected eye position errors to the right and many rightward saccades that corrected position errors to the left (Fig. 2). Although M. B. showed a marked leftward drift bias during fixation without feedback, periods of both rightward and leftward drift were apparent with feedback.

With sufficient practice using auditory feedback, subjects were able to hold the
Fig. 4. Eye position records. a to c, Two amblyopes’ attempted steady foveal fixation after auditory feedback was turned off. Auditory feedback remained off for the rest of each of these records. b and c, Records obtained 1 month apart from the same subject. Noticeably improved fixation is apparent in the later record (c) both with and without auditory feedback signals present. The asterisk in b indicates a zero adjustment made by the experimenter to bring the trace back on scale. Toward the end of c, the subject was instructed to look directly at calibration targets that were leftward (L), rightward (R) and centered (C) with respect to the position of his (projected) fovea. The trace indicates that he responded by shifting fixation to his eccentric-fixation locus. d, Another record of the same subject’s fixation after turning off the auditory feedback; steady foveal fixation was maintained until the field was darkened. Relumination of the field resulted in prompt resumption of steady foveal fixation, which hardly changed when auditory feedback was later turned on. Calibration bars to the left of each trace are 6°; time scale is in seconds.

The amblyopic eye within the deadband for many seconds at a time (Figs. 1 to 3). Periods of fixation within the deadband showed drifts in one direction and saccades in the opposite direction (e.g., Fig. 1, d), drifts and saccades in both directions (e.g., Fig. 3, a), or slowly oscillating drifts not interrupted by saccades (e.g., Fig. 3, b). All these eye movements were typically very much smaller than the width of the deadband. For this reason, they stand in sharp contrast to the larger eye movements that re-aimed the eye to the deadband after auditory feedback signaled a position error and, even more so, to the...
Fig. 5. Two amblyopes' oculomotor pursuits of a target sinusoidally oscillating at 0.125 Hz (f) are shown before auditory feedback was provided (a and d) and after (b and e). c, Subject J. F.'s improved amblyopic eye tracking performance continued for about 8 cycles after auditory feedback was turned off. Left-hand calibration bars are 6°; the time scale is in seconds.

coarse eye movements seen during amblyopic fixation without feedback (Fig. 1). We believe it is reasonable to attribute these small eye movements during steady fixation partly to the clicking signal that occurred when the eye was at or crossed through exact fixation, i.e., the center of the deadband. Whatever their origin, these small-amplitude eye movements were similar to those evidenced during fixation with the preferred eye and indicated a startling ability for fine oculomotor control which was not manifest during amblyopic eye fixation without auditory feedback.

On several occasions, we asked and succeeded in getting subjects to maintain steady foveal fixation after auditory feedback was turned off. The amblyopic eye of one subject (P. F.) was remarkably steady for approximately 15 sec without feedback before fixation drifted leftward and became unsteady (Fig. 4, a). The success of a second subject
(D. W.) in maintaining steady foveal fixation after feedback was turned off was compared for two experimental trials, 1 month apart. On the first of these trials (Fig. 4, b), D. W. had difficulty holding steady fixation even while the feedback was on. When the feedback was turned off, the left eye drifted rapidly rightward (nasalward), necessitating a zero adjustment to bring the trace back on scale. Improvement in D. W.’s fixation with feedback was evident on the later trial (Fig. 4, c); when feedback was turned off, there was little if any change in the quality of fixation. Steady fixation without feedback was maintained for about 20 sec, at which time D. W. was instructed to fixate a target (L) 3° to the left of the central fixation target. The resulting rightward eye movement indicated that he fixated this target with his eccentric-fixation locus (about 4.5° nasal and 3° superior). D. W. continued to fixate with his eccentric locus when subsequently instructed to look at a central target (C) and at one 3° rightward (R). Interestingly, fixation with the eccentric locus was steadier than it had been previously that day without auditory feedback (Fig. 1, b). The results from these two amblyopes strongly suggest that practicing steady foveal fixation with auditory feedback carries over as an improved ability to fixate with the fovea of the amblyopic eye after feedback has been turned off. That the improved monocular fixation which persists with discontinuance of the auditory signals is determined by visual error signals was supported by the immediate worsening of fixation upon darkening of the field (Fig. 4, d).

In addition to using auditory feedback to control fixation of a stationary target, we used a similar procedure to facilitate accurate foveal tracking of a target slowly oscillating horizontally in sinusoidal motion. We were particularly interested in targets moving slowly, since we reasoned that amblyopic eye fixation unsteadiness would contribute significantly to the poor tracking performance of amblyopic eyes for low velocities. Further, since we had already shown that auditory feedback could reduce amblyopic eye fixation tremor, we expected that this feedback would significantly improve tracking of slowly moving targets. During tracking, an electronic circuit “moved” the deadband so that it remained centered on the moving target. A Landolt ring oscillated at 0.125 Hz across a visual angle of 6°.

The difficulty that amblyopic eyes have in tracking slowly moving targets is demonstrated in Fig. 5, a and d. When feedback was turned on, tracking performance of J. F.’s amblyopic eye was quite poor for several cycles, after which it seemed to “lock onto” the feedback—producing accurate tracking (Fig. 5, b). After feedback was turned off, J. F. continued to track the target reasonably accurately for 60 sec or 8 cycles (Fig. 5, c). A second amblyope, M. B., also showed considerably better tracking performance with auditory feedback (Fig. 5, e). Especially noteworthy for M. B. with feedback are the many intervals of smooth pursuit from left to right which were seldom observed when he attempted to track without feedback. Both subjects were clearly able to transfer their auditory-controlled fixational abilities from the stationary-target situation to a target oscillating sinusoidally at 0.125 Hz—the transfer occurring within a few seconds on the first trial.

Discussion
Our results show that adults having amblyopia since early childhood can within a few hours utilize auditory information about eye position error to fixate steadily and foveally with the amblyopic eye. This rapid improvement of an oculomotor problem associated with amblyopia that has persisted for many years may be unexpected. The rapidity may not be surprising when one considers that in everyday life amblyopes rarely fixate monocularly with the amblyopic eye. When such fixation does take place, the abnormal eye movements and perhaps even the eccentric eye position that are observed may simply reflect a relative inability of the oculomotor control system to operate effectively with the impaired sensory inputs from the amblyopic eye.

Restated, the amblyope’s oculomotor system, which habitually operates upon information derived from the preferred eye, may
respond inappropriately to the visual error signals generated in the amblyopic eye. That there are visual error signals available during monocular viewing by amblyopic eyes is clear; these eyes do not wander aimlessly to the extremes of the visual field but rather remain aimed in the general direction of a visual target. Extensive practice in using the visual error signals from the amblyopic eye to aim the eye toward visual objects in different spatial directions may underlie, at least in part, the effectiveness of occlusion and orthoptic therapies. Our auditory feedback technique provides the amblyope with accurate error signals that can be promptly used to aim the amblyopic eye properly. Thus we tend to view auditory feedback as a means of accelerating the improvement of oculomotor performance which occurs gradually with some therapies. Of course, we do not rule out that these therapies may also effect sensory improvements in the amblyopic eye, which could in turn render visual error signals from that eye more useful to the oculomotor system.

In order for auditory feedback to produce improved fixation for an amblyopic eye, concentrated attention to auditory cues, even at the expense of visual error signals, is required initially. Simply turning on the auditory signals of eye position would not be expected to result in an immediate or automatic suppression of the visual error signals from the amblyopic eye. Indeed, many of our subjects volunteered information suggesting conflict between the auditory and visual signals. The more severe amblyopes, whose visual error signals were presumably more degraded, tended to find it easier to fixate steadily with auditory feedback than did milder amblyopes, for whom visual and auditory cues were presumably more in competition. In this connection, we note that when auditory feedback was added, Smith's normal subjects fixated slightly worse on a well-defined target and considerably better on ill-defined ones.

Although auditory signals of eye position may initially dominate the visual error signals, it is important to realize that other visual inputs are not suppressed during fixation with auditory feedback. During periods of feedback our subjects adjusted acuity targets and set contrast thresholds for gratings. The sensory judgements made during steady foveal fixation with auditory feedback were as good as or better than those made without feedback. For this feedback technique to be successful, the subjugation of visual error signals to auditory cues must subside at some point during training so that the auditory signals can facilitate proper oculomotor responses to the visual error signals.

Such facilitation of visually determined oculomotor responses may have been demonstrated in our study when the auditory feedback was turned off and the amblyopic eye continued to fixate steadily and foveally. This fixation, consisting of oppositely directed small amplitude drifts and saccades, was qualitatively normal in character and appeared to be driven by visual errors. That visual errors were responsible for these post-auditory feedback fixation patterns is demonstrated by the immediate worsening of the fixation pattern upon darkening of the field. The transfer of improved monocular fixation of the amblyopic eye to circumstances without auditory feedback is encouraging because it suggests the possibility of long-term and perhaps permanent correction of the oculomotor deficits of amblyopic eyes.

The complete correction of the abnormal fixation behavior of an amblyopic eye would also require a shift of the directional reference (oculomotor zero) point from the eccentric-fixation locus to the fovea. One of our subjects (M. B.) had a change in the magnitude of his temporal eccentric fixation (from 3° to 1° as measured by Maxwell's spot) over a 7-month period during his participation in our experiments. Associated with this change in his eccentric fixation was a corresponding shift in his directional reference point as determined by his subjective designation of where on the screen his eye was aimed.

Indeed, all our eccentrically fixing amblyopes reported that in order to direct Maxwell’s spot to a fixation target, they felt as if they were looking off to one side of the
target by an amount approximating the angle of eccentric fixation. Although this sensation often persisted with auditory feedback, several subjects reported that on occasion while fixating with feedback, they either became uncertain as to where the eye was directed or felt they were looking directly at the fixation target. These observations serve to clarify our use of the term "foveal fixation" under conditions of auditory feedback, which until now we have employed to mean an aiming of the fovea at a fixation target and an attending to that target. The above observations indicate that foveal fixation with correct directionalization was established on occasion for some subjects using the feedback technique.

In evaluating the possible benefit of our auditory feedback procedure for improving fixation steadiness of amblyopic eyes, it is worth considering what has been accomplished by others by simply having subjects inhibit their saccades. Sophisticated25 and naive26 subjects with normal vision as well as amblyopes11 were given special fixation instructions that resulted in inhibition of saccades. In addition, some amblyopes were given either a verbal or a clicking sound indicating when a saccade occurred.10 For both normal and amblyopic subjects, the main result seems to be consequent excursions of the eye over approximately the same range as before the instructions but with the total motion of the eye being reduced due to the predominance of slow-moving drifts rather than rapid saccades (which were inhibited). The total ocular motion was reduced more for the amblyopic eyes because inhibition of the saccades included the frequent error-producing saccades characteristic of these eyes. By contrast, practice with our auditory feedback procedure resulted primarily in a reduced range of ocular excursions with a selective reduction of error-producing saccades (fovea moves away from target) but retention of error-correcting saccades (fovea moves toward target). In addition to steadying the monocular fixation tremor of amblyopic eyes and making the movements qualitatively more normal-appearing, the auditory feedback procedure here described has the further capability of shifting fixation from an eccentric locus to the fovea.

We have noted that amblyopic eyes can also utilize the visual feedback provided by Maxwell's spot to help steady fixation with the fovea. This phenomenon was most often noted for experienced subjects during the calibration procedure when the subject aimed the fovea (Maxwell's spot) between pairs of fixation targets without auditory feedback. We believe, however, that auditory feedback has several real or potential advantages over visual feedback from entoptic images for helping to steady fixation. The advantages of auditory feedback are that (1) it does not require special conditions of visual stimulation and does not introduce extraneous visual stimuli that can interfere with foveal viewing or testing, (2) it can be used with subjects who do not perceive foveal entoptic images with the amblyopic eye—calibration being done instead with a blindspot fixation technique (Fig. 1, b), (3) auditory feedback is not subject to fading or intermittent perception as are entoptic images and afterimages, (4) it is perceptually more commanding than low contrast entoptic images, and (5) unlike entoptic images, the auditory feedback is subject to experimental monitoring and control. The only significant limitations we see for auditory feedback are that (1) the head must be restrained (as with a bite bar) or, if the head is allowed to move somewhat (as with a chin cup and/or headrest), head and eye movements must be electronically separated, (2) the technique requires somewhat complicated and costly equipment, and (3) in its current form, only horizontal eye position errors are signaled to the observer, leaving possible residual vertical fixational inaccuracies. Since amblyopes' fixational unsteadiness can usually be resolved into large horizontal and much smaller vertical components and since initial equipment costs might be offset by rapid progress during training, we conclude that the benefits of auditory feedback significantly outweigh the limitations.

To date, this auditory feedback technique has been used primarily to obtain psychophysical measurements at known retinal lo-
cations in functional amblyopic eyes. In addition, subjects with congenital nystagmus have used this auditory feedback in our laboratory with success in reducing the amplitude and frequency of their spontaneous eye movements.) As a matter of convenience, we have so far studied only adult amblyopes because they cooperate well and readily tolerate the inconvenience of a bite bar, extended experimental sessions, and sensing equipment placed close to the eyes. We have not yet determined the experimental conditions that are optimal for amblyopic eyes to acquire steady foveal fixation with auditory feedback or to sustain their improved oculomotor performance in the absence of auditory cues. We now plan to explore the therapeutic value of this feedback technique and to modify the technique to be suitable for children. We have already established that a 4-year-old with normal vision can appropriately modify his fixation in response to auditory feedback cues. By extending our efforts to therapy, adult amblyopes will continue to be included since they also are amenable to treatment.

REFERENCES


