Auditory Biofeedback to Control Vertical and Horizontal Eye Movements in the Dark

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Although there is evidence demonstrating the effectiveness of oculomotor auditory biofeedback on the control of the horizontal component of gaze in the dark, the oculomotor behavior of the horizontal and vertical components under such conditions remained unknown. Horizontal and vertical fixational eye movements were measured monocularly using an infrared limbal eye tracker in three normal subjects under three conditions: in the light, total darkness, and total darkness with two-dimensional auditory biofeedback of the eye movement. With fixation in the light, all subjects showed small drifts and corrective movements of up to about 0.5° horizontally and vertically. With fixation in total darkness, the eye movements generally exhibited drifts and saccades of well over 2°. However, with auditory biofeedback added during fixation in total darkness, the drifts and corrective saccades were reduced to levels more similar to those found with fixation in the light. The percent time on target in the light, dark and dark plus auditory biofeedback conditions was about 100, 50 and 80%, respectively, for both horizontal and vertical eye position. These results demonstrate that incorporation of two-dimensional oculomotor auditory biofeedback alone is sufficient to maintain fixation accuracy of both horizontal and vertical eye movements in total darkness close to that found during normal fixation in the light.

Auditory Biofeedback

The control of physiological functions by means of biofeedback has been used in many applications as an adjunct to conventional medical therapy. Probably the most common application of biofeedback involves stress reduction by monitoring a number of physiological functions apparently related to stress. For example, one's muscle tension, which is well correlated with overall stress level, can be monitored electromyographically and made available to the subject to develop control over his stress level.1

There have also been numerous ophthalmic applications of biofeedback for the correction of oculomotor abnormalities and/or improvement of oculomotor functions.2 3 For example, auditory signals related to eye movement have been used successfully in oculomotor biofeedback therapy to control abnormal eye position and movement in strabismus, nystagmus and amblyopia.4 10 These auditory oculomotor biofeedback training procedures provide the subject with tonal information related to eye position and movement characteristics. Thus, both continuous visual and auditory feedback are available to the subject to control fixation.

The fundamental control of eye position using only auditory information was first investigated by Smith.11 He used a photoelectric eye movement method to record horizontal eye movements in normal subjects with and without auditory biofeedback both in the presence and absence of visual feedback. One task was to have the subject maintain fixation at the center of three horizontally positioned lights. The peripheral lights were 1.2° from the central fixation light. Eye movements were recorded both with and without auditory biofeedback. The lights were then extinguished, and the subject attempted to fixate the previously illuminated center light. Eye movements were recorded for two 30-second periods. Later, an auditory tone was added whenever eye position was within ±1.2° of the center. Smith found that the percent time on target in the light was about 83% for fixation both with and without the auditory biofeedback. The percent time on target in the dark was about 83% for fixation both with and without auditory biofeedback. In the dark, however, there was a much greater percent of time on target for attempted fixation with (42%) than without (16%) the auditory biofeedback. Unfortunately, no eye movement traces were shown in this report.

The purpose of the current study was to investigate the effect of horizontal and vertical oculomotor auditory biofeedback on fixation in total darkness. Horizontal and vertical eye movements were recorded...
under three conditions in three subjects: fixation in the light with normal visual feedback, attempted fixation in the dark without visual or auditory feedback, and attempted fixation in the dark with two-dimensional oculomotor auditory biofeedback. The results for all subjects showed that the percent time the eye was on target (ie, within the range of an auditory biofeedback window) was highest for fixation in the light, slightly lower for attempted fixation in the dark with auditory biofeedback, and considerably lower for attempted fixation in the dark without auditory biofeedback.

Materials and Methods

Subjects

Three subjects from the student population at Rutgers University were used. Ages ranged from 17 to 25 years. Each had normal visual acuity and oculomotor function as determined by standard clinical tests. None had a history of ocular or neurological abnormalities. Two subjects were emmetropic, while the third (SM) had her refractive error corrected during the experimental runs. One of the emmetropic subjects (CC) had some prior experience in oculomotor research. All subjects gave informed consent to participate in the experiments.

Experimental Set-up and Measurement

The subject was seated with the plane of the entrance pupil of the eye 114 cm from the target plane. A bite bar was used to stabilize the head during the eye movement recording. The black-on-white background target consisted of a horizontal line (14° in length) bisected by a vertical line (+/−3° in height). There were also small tick marks (1° in length) at 1° intervals along each line. All lines and tick marks were 3 min of arc thick.

Eye movements of the left eye were recorded by means of the infrared reflection technique. A patch was worn over the right eye. Horizontal eye movements were recorded by the subtraction of signals from the photodetectors placed in front of the nasal and temporal limbal regions in the horizontal plane. Vertical eye movements were recorded by the summation of signals from the photodetectors placed at the nasal and temporal limbal regions slightly below the horizontal plane. For horizontal eye movements, this technique provides a resolution of about 10 min of arc with a linear range of about ±10°. We also found this range of linearity in previous experiments in our laboratory using the horizontal photodetectors. Vertical eye movement resolution using this technique is typically about 15 min of arc with a linear range of at least ±2°. As we were primarily concerned with eye movements within the small bio-feedback window, we restricted the pre-experimental check to ±2° horizontally and vertically and found linearity within this range for all sessions.

The auditory biofeedback was controlled by a circuit which allowed the experimenter to manipulate the upper and lower limits of the voltages (corresponding to the eye position changes in degrees) that gated the eye movement signal. If the horizontal eye position voltage was within the horizontal limits or the vertical eye position voltage was within the vertical limits, an audio output was produced. For horizontal eye movement within the horizontal extent of the window, the audio output was a 5 “clicks”/second sound. For vertical eye movements within the vertical extent of the window, the output was a low frequency (~500 Hz) continuous tone. The two 8 ohm speakers (for “clicks” and “tone”) were placed about 2 feet in front of and 30° to the left and right of the subject, respectively. Both speakers were tilted upward so that the sound was reflected diffusely from the ceiling. These two different sounds allowed for the differentiation of horizontal from vertical auditory biofeedback signals by both the subject and experimenter.

The outputs of the horizontal and vertical eye movement monitors were recorded on disk using a PDP-11/40 computer (Digital Equipment Corp., Maynard, MA). The sampling rate of each 3-second record was 171 Hz. For each subject, about 100 to 200 total records (equally divided for the three conditions) were obtained and used for the calculation of percent time on target (ie, the amount of time when monocular gaze was within the biofeedback window during a 3-second record). An analysis program was used to calibrate the responses and edit the data. Records containing artifacts such as a large number of blinks were deleted. The resulting horizontal and vertical eye movement data were plotted on a Calcomp plotter (California Computer Products, Inc., Anaheim, CA). By examining the eye movement records, the experimenter could determine when the auditory biofeedback was on (for example, within ±1°) and when it was off (outside of ±1°).

Procedure

The subject first made saccadic eye movements of ±1° and ±2° both horizontally and vertically for the purpose of determining the calibration and linearity. Then the subject either fixated in the light or attempted to fixate in total darkness with and without the two-dimensional auditory biofeedback. The fixation periods were generally 100 seconds in duration. The three test conditions were randomized.

To demonstrate that fixation in the dark with auditory biofeedback could be accomplished both in and
out of primary position, we used two fixation paradigms. In the first, the eye was allowed to drift in the dark for several seconds until a steady-state position was attained (eg, subject CC tended to drift to the right), and in that vicinity the auditory biofeedback window (±1° horizontally and vertically) was electronically positioned by the experimenter. The total amount of this drift was generally greater than 2° horizontally and less than 2° vertically from central fixation in primary position. In the second paradigm, fixation was in primary position, with an auditory biofeedback window of ±1° horizontally and ±2° vertically. The larger vertical range was empirically determined and reflected the increased variability of attempted fixation in the dark in primary position. Subject JC was tested in the first paradigm only.

In the dark without auditory biofeedback, subjects were instructed to imagine looking straight ahead. On the other hand, under both paradigms for fixation in the dark with auditory biofeedback, subjects were instructed to imagine looking at and maintaining the eyes within the biofeedback window. Generally, the subject first made large eye movements past the window, thus obtaining a brief burst of sound. Then by reducing the amplitude of these movements, the subject obtained longer and longer durations of sound as he/she homed in on the window. The subjects found it easier to use the horizontal auditory biofeedback ("clicks") first to get within the horizontal boundaries of the window, and then use the vertical auditory biofeedback ("tone") and a similar strategy to get within the vertical boundaries of the window. In no instance, except transiently and by chance, did the subject's fixation fall within the two-dimensional window when he/she used the auditory biofeedback in only one dimension.

A total of about 100 3-second records constituted one session. An entire session, including set-up and rest intervals, required about 1 hr to run. During the rest interval in the dark, subjects were allowed to close their eyes but remained on the bite bar. All subjects participated in at least one practice session. Subject JC participated in one experimental session, while the other two subjects each participated in two experimental sessions.

For fixation in the dark, an enclosure (2 cubic feet) was placed over the subject to prevent stray light from the equipment gauges from entering the test field. Subjects did not report seeing any light during this portion of the experimental sessions.

Results

Representative horizontal and vertical eye position traces are shown in Figures 1–3 for the three test conditions in each subject. Note the relatively stable horizontal and vertical eye position for fixation in the light, and the slightly more variable movements during attempted fixation in the dark with the auditory

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**Fig. 1.** Corresponding horizontal (left) and vertical (right) eye movement traces for subject CC under the three test conditions. Three representative records displayed in each test condition. Upward deflections represent leftward and upward eye movements.
biofeedback. In some traces, maintained stability for up to 9 consecutive seconds was seen under both conditions. In contrast, relatively large random drift movements were evident during attempted fixation in the dark without the auditory biofeedback. Vertical eye movements had about the same amplitude as horizontal movements and did not necessarily occur in synchrony with them.
Table 1. Percent time on target and RMS error

<table>
<thead>
<tr>
<th>Subject</th>
<th>Paradigm</th>
<th>Light</th>
<th>Dark</th>
<th>Dark + biofbk.</th>
<th>Light</th>
<th>Dark</th>
<th>Dark + biofbk.</th>
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<tr>
<td>CC</td>
<td>1</td>
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<td></td>
<td></td>
<td>(0.17)</td>
<td>(1.13)</td>
<td>(0.54)</td>
<td>(0.30)</td>
<td>(1.86)</td>
<td>(0.61)</td>
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<td></td>
<td>2</td>
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<td>50</td>
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<td>76</td>
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<td></td>
<td></td>
<td>(0.24)</td>
<td>(1.57)</td>
<td>(0.48)</td>
<td>(0.43)</td>
<td>(1.52)</td>
<td>(0.75)</td>
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<td></td>
<td></td>
<td>(0.39)</td>
<td>(1.20)</td>
<td>(0.45)</td>
<td>(0.27)</td>
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<tr>
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<td>100</td>
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<td>63</td>
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<td></td>
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<td>(0.36)</td>
<td>(1.10)</td>
<td>(0.50)</td>
<td>(0.29)</td>
<td>(1.04)</td>
<td>(0.47)</td>
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<tr>
<td>JC</td>
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<td>53</td>
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<td>92</td>
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<tr>
<td>Composite data (Smith)</td>
<td>Similar to 2</td>
<td>83</td>
<td>16</td>
<td>42</td>
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Percent time on target and root mean square (RMS) error (in parentheses in units of degrees) for horizontal and vertical eye position for the three subjects. Also included is the composite data from Smith.11

The traces presented above were representative of those using the first fixation paradigm in which the subject's steady-state position in the dark was compensated electronically by the experimenter. Results for the second fixation paradigm (ie, primary position) were similar. A comparison of percent time on target (ie, within the auditory biofeedback window) between the two paradigms is presented in Table 1. The percent time on target was similar for the two paradigms, although the vertical biofeedback window used for "capture" of eye movement was larger in the second paradigm. Once captured, however, the drift movements frequently remain within the window for several seconds.

Quantitative analysis of the results was also performed in two other ways. First the individual records for each condition were combined as a time series, and the root mean square (RMS) deviation was calculated. The length of a time series was equal to the number of records for a particular condition times 512 points/record. The results are tabulated in Table 1. For all subjects and for both horizontal and vertical eye movements, the RMS value was largest for the condition of fixation in the dark, smallest for fixation in the light, and intermediate for fixation in the dark with auditory biofeedback. Second, a two-way repeated measures, within-subjects analysis of variance was performed for each fixation paradigm for the factors of direction of eye movement (horizontal and vertical) and test condition (light, dark, and dark plus auditory biofeedback). For paradigm one, there was no effect of direction of eye movement [F(1,1) = 1.5599, P > 0.10], but there was an effect of test condition [F(2,2) = 529.0666, P < 0.01]; there was no interaction [F(2,2) = 0.3232, P > 0.10]. Similarly, for paradigm two, there was no effect of direction of eye movement [F(1,1) = 0.2010, P > 0.10], but there was an effect of test condition [F(2,2) = 529.0666, P < 0.01]; there was no interaction [F(2,2) = 0.3232, P > 0.10]. Thus, the statistical analysis confirmed and extended our conclusions based on the RMS analysis.

Discussion

This investigation extended the study of Smith11 by recording both vertical and horizontal eye movements, as well as using an additional fixation paradigm. The horizontal eye movement results of the current study are in general agreement with those of Smith.11 However, his subjects' percent time on target both with and without auditory biofeedback were lower than those found in this study. This may reflect differences in motivation and/or training of the subjects involved, or perhaps differences in experimental conditions. For example, Smith did not indicate whether a bite bar was used to stabilize the subject's head. The lack of eye position time traces in Smith's report,11 however, prevents us from comparing dynamic characteristics of eye movements under the various test conditions. On the other hand, a comparison with Stark's14 data showing two-dimensional fixation in the light without auditory biofeedback shows results similar to ours. Also, the data of Skavenski and Steinman15 exhibited similar variations of vertical and horizontal eye position during attempted fixation in the dark without auditory biofeedback.

When compared to fixation in the light, fixation in the dark may contain additional sources of errors in localization. First, if a subject has a "physiological position of rest" (ie, tonic vergence) that is not coincident with the primary direction, this neural bias.
toward some eccentric position may be especially potent in the dark, without normal visual feedback. Second, an erroneous perceptual estimate of target position in the dark may produce an additional error. The ability to control eye movements in both the horizontal and vertical directions in the dark with auditory biofeedback reveals the diverse neural control pathways available to an individual. The use of auditory signals and the interpretation of spatial direction under such conditions probably requires input from higher cortical centers. The moderate reduction in accuracy of fixation using auditory biofeedback in the dark versus normal visual feedback in the light may be attributed to vagueness of one’s spatial frame of reference under such conditions. Indeed, fixation of a small visible target in the dark, with the reduction in cues to the frame of reference, gives rise to autokinesis.

Lastly, the findings have considerable potential clinical impact. As mentioned earlier, oculomotor auditory biofeedback has been used successfully to control horizontal eye position and motion in a variety of ophthalmic and neurologic conditions, including amblyopia, strabismus and nystagmus. Frequently, there is a significant vertical component to the oculomotor abnormality, which largely has been ignored. Now, a variable auditory feedback window with discrete signals distinguishing horizontal from vertical eye position and movement can be used in such patients in attempting to control fixation as well as conjugate and disjunctive tracking movement in two dimensions, thus improving visual acuity, basic eye tracking ability, sensory and motor binocularity, and/or cosmesis. Key words: auditory biofeedback, vertical and horizontal eye movements, darkness, fixation, visual feedback, oculomotor control

Acknowledgment

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References