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Effect of Eye Movements on Dynamic Equilibrium

DIANA L. SCHULMANN, BETSY GODFREY, and ANNE G. FISHER

The purpose of this study was to determine whether visual improvement of balance varies depending on the movement of the eye. Three movements were compared: static visual fixations, saccadic eye movements, and smooth pursuit eye movements. The subjects in this study were 35 healthy female volunteers. Balance was defined as the subjects' ability to maintain their equilibrium while keeping the unstable platform on which they stood within 5 degrees of the horizontal plane. The testing protocol consisted of five recorded practice trials, during which the subjects tried to maintain their balance without any visual instructions, and nine experimental trials, during which they tried to maintain their balance while visually following a videotaped target light projected onto a screen. The target light was sequenced randomly to remain stationary, move in a continuous horizontal path, or alternately jump between right and left. Data were analyzed using a one-way multivariate analysis of variance for repeated measures. A significant effect of vision on balance was found. The f tests for correlated samples revealed that time in balance during visual fixations and saccades was significantly longer than during tracking eye movements. We, therefore, concluded that tracking eye movements have a negative effect on balance. This information can be useful in treating patients with balance problems. For example, instructing patients to fixate visually on an object may aid their stability. Visual tracking of a moving limb, however, may impair a patient's stability.

Key Words: Equilibrium, Eye movements, Physical therapy.

Vision has a primary role in governing spatial orientation and balance. Monitoring body position relative to the external world by vision enables an individual to detect and react to very slight shifts in body position. The central nervous system processes visual, proprioceptive, and vestibular signals to enable the individual to react efficiently to very slight postural shifts. Despite a vast amount of evidence indicating that equilibrium responses are highly dependent on vision and that patients with neurological disorders often demonstrate visuomotor impairments and motor deficits, therapists seldom are concerned with the visual status of their patients. Furthermore, therapists rarely monitor or direct patients' visual activity during therapy. An understanding of the relationship between eye movements and motor control can advance treatment efficacy for patients who are unstable posturally. The purpose of this study was to determine whether balance is affected by different types of eye movements.

How do vision and eye movements contribute to postural maintenance? As a person shifts position, the visual scenery (field or surround) appears to move in the direction opposite to the head movement. The CNS perceives this visual field motion as resulting from self-motion and immediately executes appropriate postural adjustments. For visual field movement to be perceived accurately, the eye first must have viewed the visual field as stationary. One class of eye movements interferes with this initial stable image of the visual field and, therefore, could preclude visual mediation of posture. Other eye movements that depict the environment as stable could enhance stability.

Individuals have three visuomotor options given a stationary visual surround. They voluntarily can move the eyes using saccades. These are quick (400°-600°/sec) eye movements from one fixation point to another. Saccades are used to scan a stationary environment or to read. They are the only eye movements that depict the environment as absolutely despite eye movement. The eyes can track (follow) a moving target is visible, in which case smooth pursuit eye movements (SPEMs) are possible. The eyes can track (follow) a moving stimulus by using these slower (1°-30°/sec) eye movements. Visual fixation on a stationary object is a third possible visuomotor activity.

Movement perception differs depending on the type of eye movement. During both saccades and visual fixations, the visual surround appears to be fixed absolutely despite eye movement. During SPEMs, however, the eyes register the perceived movement of the visual field caused by the movement of the eyes. The image of the moving object remains stationary on the fovea, whereas the static background, the peripheral visual field, appears to move.
Visual fixation and saccadic eye movements, which suppress visual field motion perception, should enhance the visual signal of self-motion. Improved sensation of small body movements then would facilitate the execution of compensatory equilibrium reactions. The SPEMs, however, might impair visual signals of self-motion by disturbing the visual field stillness. The loss of the effective visual signal of self-motion would be expected to interfere with normal equilibrium reactions.

Edwards et al. reported that postural sway was increased when subjects visually tracked a swinging pendulum as compared with when they fixated, but did not examine the effects of saccadic eye movement. Iwase et al. and Uchida et al. demonstrated that saccades reduced static postural sway when compared with visual fixations and passive eye rotation.

Because saccadic eye movements and visual fixations preserve the stable image of the environment, we hypothesized that they would promote postural stability during standing, whereas SPEMs would impede it. To examine the effects of eye movement on balance, we tested subjects performing a dynamic and difficult balancing task. Successful performance on the testing apparatus demanded oculomotor control; attention; and the integration of visual, vestibular, neck, and ankle proprioceptive signals. A challenging task was chosen purposely to attempt to more closely simulate the problems of a patient with neurologic impairment. By positioning healthy subjects on an unstable base of support, we imposed a state of disequilibrium and effectively handicapped them. This experiment was a means of exaggerating the otherwise automatic task of balancing and further legitimizing inferences about a specific patient population.

METHOD
Subjects

The subjects in this experiment were 35 healthy female volunteers, aged 18 to 35 years. We selected subjects of the same sex because earlier studies have revealed sex-related differences in balancing. The subjects were taking no medications that affected equilibrium and had no history of balance problems, no abnormal sensation in the lower extremities, and no history of frequent fainting.

We also selected subjects with no history of visuomotor impairment, amblyopia ("lazy eyes"), nystagmus, or other abnormal eye movements. Although we had intended to monitor eye movements with electro-oculograms, time and funding constraints necessitated that we adopt an alternative method. Because the movements we elicited were large, slow, and regular, we found that we could see the subjects' eyes easily and thus determine whether they were responding appropriately to the stimulus.

Instrumentation

A stability platform was used to measure balance. The stability platform was an unstable horizontal platform that was movable in the frontal plane. Balance was defined as the subjects' ability to maintain their equilibrium while keeping the unstable platform on which they stood within 5 degrees of the horizontal plane. Two microswitches were activated to stop a timer when the angle of tilt exceeded 5 degrees.

The visual stimuli were produced by programming a Commodore 64 computer to move a 3-mm target light in three different patterns. A 0.25-Hz square wave pattern was used to induce saccades in the horizontal plane. The waveform generated two alternating lights, each appearing for two seconds' duration. The SPEMs were induced using a 0.25-Hz sinusoidal wave pattern. This pattern produced horizontal cursor movement across the screen. At each end of the cursor's path, the velocity was attenuated. The peak velocity, in the center of its path, was 47°/sec. We used a frequency of 0.25 Hz for both the saccadic and the SPEM conditions because it was within the range of both types of eye movements. The moving cursor evoked eye movements (saccades and SPEMs) subtending an arc of 30 degrees. For the visual fixation condition, the cursor remained centered on the screen.

All stimuli were videotaped and projected at eye level onto an approximately 1.5-m (5 ft) wide Sony KP 7200 front projection television screen using a JVC VHS videocassette player. During the practice and experimental trials, the lights in the room were dimmed to maximize the contrast, but were kept sufficiently bright to allow the experimenters to maintain a clear view of the subjects' eye movements.

Procedure

We explained the objectives of the study to the subjects, and they read and signed an informed consent statement. Shoulder width, or the distance between the acromion processes, then was measured by tape measure, and the distance was marked on the testing platform. We directed the subjects to place their feet just outside the marks and to keep the platform evenly balanced (horizontal) for as much time as possible. They then balanced the platform for five 30-second periods, each separated by 30-second rest intervals. The last 20 seconds of each of these practice trials was recorded, allowing 10 seconds for orientation.

After the five practice trials, the subjects were seated, and the testing procedure was explained. They were instructed not to move their heads, not to anticipate the movement of the light, and to allow the light to "lead the eye" across the screen. To practice the eye movements, the subjects stood still on the platform and received verbal feedback about both eye and head movement. When they demonstrated proficiency in the eye movements, we began the experimental trials. The visual stimuli were presented in a random sequence.

A total of nine experimental trial recordings were made. Each trial was 30 seconds in duration, but only the last 20 seconds were measured. If the subjects moved their heads, they were reminded to keep still and the experimenter recorded the movement. Occasionally, the subjects' eyes would make a saccadic movement away from the stimulus. If more than three of these deviations occurred, the trial was excluded from the data analysis. After all the trials were completed, the subjects indicated which condition they found most difficult to perform.

Data Analysis

We calculated the means and standard deviations of the time in balance for the three visual conditions. Because the sample comprised nonrandomly selected volunteers and because the intercorrelations between the dependent variables were significant (r = .66), we
then performed a Bartlett test of sphericity to determine whether a significant lack of homogeneity of variance existed. The results of the Bartlett test of sphericity were significant ($p = .000$), indicating that the hypothesis of homogeneity should be rejected and that the data should be analyzed by a multivariate analysis of variance (MANOVA), which is more powerful under such conditions. The one-way MANOVA for repeated measures tested the hypothesis that eye movement would have a significant effect on time in balance.

**RESULTS**

Table 1 shows the means and standard deviations for the five practice trials. The measurements of time in balance increased for the first three trials and then leveled off, indicating that the subjects learned the task after three trials. Means and standard deviations for time in balance under each of the three visual conditions (saccades, SPEMs, and visual fixations) for the 35 subjects in the experimental trials were computed and examined for "outliers," or measurements greater than two standard deviations from the mean. One subject's measurements consistently fell more than 2 standard deviations below the mean and, therefore, were eliminated from further analyses. The recalculated means and standard deviations for the balancing times during each eye movement of the remaining 34 subjects are shown in Table 2.

The MANOVA revealed a significant visual effect (Wilke's Lambda = .42; approximate multivariate $F = 22.01; df = 2.23; p = .000$). Because the MANOVA procedures do not generate values for mean square within or between conditions, we were unable to perform post hoc multiple-comparison tests. We instead used $t$ tests for correlated samples to locate significant differences in mean values between conditions. The accepted level of significance was .05.

<table>
<thead>
<tr>
<th>Eye Movement</th>
<th>Time in Balance (sec)</th>
<th>X</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saccades</td>
<td>11.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Visual fixations</td>
<td>10.8</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Smooth pursuits</td>
<td>9.7</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

- * $p < .05$, saccades × smooth pursuit eye movements.
- ** $p < .05$, visual fixations × smooth pursuit eye movements.

Analysis of the data revealed that time in balance during saccades and visual fixations was significantly longer than time in balance during SPEMs. We found no difference in time in balance between saccades and visual fixations. These results were supported by the subjects' subjective reports, the majority (75%) of whom indicated that balancing during SPEMs was the most difficult task to perform. Sixty-five percent of the subjects reported that balancing while fixating was the easiest task to perform.

**DISCUSSION**

We interpreted these results as support for the hypothesis that saccadic and visual fixation eye movements strengthen, and SPEMs weaken, dynamic equilibrium control. An explanation for the strong relationship between eye movements and balance is that the visual control of balance depends on visual perception of a still environment. An individual can determine self-motion by using the surround as a reference. The field motion produced by a shift in body position signals the need for compensatory body movement to reorient the body to the vertical plane. Visual fixation and saccadic eye movements elicit a steady image against which postural shifts can be discerned. The SPEMs, which depict the surround in motion, prevent this potent feedback.

An explanation for this differential ability of eye movements to facilitate balance may be that each has evolved to subserve a separate function. The visual system often is thought of as comprising two systems, central and peripheral. Peripheral vision is used for spatial orientation. Visual fixation and saccadic eye movements maximize peripheral vision by affording a stable visual field. Central vision functions in object analysis. The SPEMs, used to track and maintain the image of a moving object on the fovea, subserve the central analytical function, but may be inappropriate for spatial orienting purposes.

The basis of field motion inhibition during saccadic and visual fixation eye movements is not understood fully. These eye movements probably have a common origin. Either this neural generating mechanism or a peripherally evoked phenomenon controls saccadic suppression. They demonstrated that the high speed of these eye movements was not the source of the suppression. They compared saccadic eye movements with peripheral field movement and found that central saccadic suppression of field motion stimulated reductions in postural sway. Others have suggested that the stabilizing effect of saccades lies in a central (reticular activating system) postural control locus that incorporates these eye movements. The evidence presented for this explanation was that saccades elicited with the eyes closed still could reduce sway. Such a rationale is questionable, however, because the act of closing the eyes, itself, may alter the visual gain.

Romberg first noted that vision can compensate effectively for vestibular or proprioceptive deficiencies. Therapeutically, however, vision rarely is considered to be a primary instrument for controlling balance. Our results show not only that eye movement can affect equilibrium, but also that the effect varies as a function of the type of eye movement. Romberg's claim that vision stabilizes the body, therefore, does not explain adequately the complex process of visual postural control. Just as it is important to determine what components of the vestibular system are affected by a treatment (eg, otoliths or semicircular canals; static or phasic), it also is important to clarify the type of eye movement that accompanies any eyes-open condition.

These findings can be applied directly to physical training situations. Visuo-motor education should be encouraged to enhance the equilibrium responses of patients with balance deficiencies secondary to cerebellar and vestibular ataxia, stroke, and such diseases as tabes dorsalis and parkinsonism. Patients who are posturally unstable might be trained to scan their field of vision using reflexive saccades or to maintain visual fixation on a stationary object in the environment to enhance their equilibrium.
reactions. The potentially detrimental effects of using SPEMs to track self-motion should be avoided in patients with postural instability. Specific visuomotor evaluation and training to develop ocularmotor stability in patients with an impaired ability to fixate accurately, perform saccadic eye movements, or visually track moving objects should have a secondary effect on gait and balance-reaction training. Finally, visuomotor training may be incorporated inappropriately into the treatment of patients with proprioceptive deficits. These patients sometimes are taught to compensate for lost position sense by tracking visually a moving limb through space. This practice could be self-defeating if visual tracking disturbs spatial orientation or balance.

CONCLUSIONS

The results of this study show that eye movements can determine the efficacy of visual postural control. Tracking eye movements have a negative effect on balance compared with visual fixation and saccadic eye movements. Further clinical research should be directed to 1) identifying patient populations that can benefit from combined visuomotor and balance training, 2) developing methods by which eye movements can be trained, and 3) determining the effectiveness of retraining guided limb motion with and without visuomotor direction.

REFERENCES


Commentary

The authors are to be commended for this interesting study. Physical therapists long have overlooked the use of different types of eye movements in rehabilitation, with the possible exception of the vestibulo-ocular reflex (VOR). The role of all eye movements is to either bring or maintain the target image on the fovea of the retina. Saccadic eye movements are used to shift between different targets. If the target is stationary and the head is moving, then an interaction between the VOR and the optokinetic response (OKN) stabilizes the image on the retina. Moving targets, however, smooth pursuit eye movements (SPEMs) must be used to stabilize the image on the fovea.

The perception of self-motion during SPEMs has been shown to be produced only when a sufficiently large target is moving in one direction around the individual. This perception of self-motion produces the effect called circularvection, which has a latency of a few seconds and which presumably is caused by charging of the velocity storage system in the brain stem. A similar phenomenon called linearvection occurs when large targets are moved in a sine wave pattern toward and away from an individual. Targets smaller than 30 degrees moving around an individual against a uniform background produce the perception that the environment, rather than the individual, is moving. Although the authors state that their target was 3 mm across, the distance from the subject to the target was not given. This distance would determine the actual size of the target in the visual field. Although the actual size of the target was not reported, it seems likely that it is less than 30 degrees.

Movement of small targets, such as the 3-mm target used in this study, against a heterogeneous background might result in the perception of self-motion and, therefore, require postural responses to correct for the disturbed equilibrium. To demonstrate this effect, subjects should be tested against both heterogeneous and uniform backgrounds. In this study, it is unlikely that the SPEMs resulted in either circularvection or linearvection because they were performed with a small target in a sine wave pattern against a uniform background. Because head movement was possible during the study and because the screen in front of the subjects could not fill the entire visual field, however, an OKN possibly was generated that would affect the velocity storage system. I do not think that an OKN would have a significant role under the conditions of this study. To test for that possibility, however, the authors either could eliminate the OKN by moving the target light across a Ganzfeld or they could repeat the experiment using the same design and then turn off all lights.
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