Visual Stabilization of Posture in Persons With Central Visual Field Loss

Kathleen A. Turano,* Gislin Dagnelie,* and Susan J. Herdman†

Purpose. To determine whether people with central visual field loss (CFL) show a smaller visual contribution to posture stabilization than people with normal vision and to determine the visual factors that predict the magnitude of visual stabilization in people with central visual field loss.

Methods. Posture information was recorded in 19 subjects with CFL and in 20 subjects with normal vision. Data were collected as the subject stood in a dark environment and also as he or she viewed a stationary visual display. In both conditions, somatosensory feedback was concurrently altered. The central visual fields of the subjects with CFL were measured by static perimetry with the confocal scanning laser ophthalmoscope. Binocular visual acuity and contrast sensitivity were measured on all subjects using the ETDRS and Pelli-Robson charts, respectively. Image-displacement thresholds were measured in a subset of the subjects.

Results. On average, subjects with central field loss showed a smaller visual contribution to posture stabilization than subjects with normal vision. The reduction in sway caused by visual stimuli was only 29% for the subjects with CFL compared to 41% for the subjects with normal vision. Displacement thresholds accounted for 45% of the variance in the visual stabilization magnitude of the subjects with CFL. No other visual factor significantly increased the coefficient of determination.


Postural instability has been shown to be associated with falling1–5 as well as with inefficient mobility.6 These associations underscore the importance of precise postural control for safe and efficient mobility. Although posture can be governed by information from several sensory systems—visual, vestibular, and somatosensory—the availability of visual information can reduce postural sway by as much as 50%.7

As a person stands upright within a stationary environment, the body makes small oscillatory movements. These movements produce changes in the optical structure of texture elements over the visual field. The changes indicate the direction of body oscillations relative to the environment, and, if detected, these changes can be used as cues to direct compensatory postural adjustments.

In a previous study,8 we investigated the role of visual information for posture control in a group of low-vision observers with retinitis pigmentosa (RP), a disease characterized by, among other effects, progressive visual field loss that eventually leads to severely contracted central visual fields.9 It was hypothesized that in this group of low-vision observers, visual information would contribute less to postural stability than it does in normal-vision observers. This hypothesis was based primarily on the traditional view that the peripheral visual field plays a dominant role in self-motion perception, whereas the central visual field plays little to no role.10,11 Subjects with RP did show a smaller visual contribution to postural stability than did subjects with normal vision, and the amount that the vi-
visual information contributed to stabilization was inversely related to disease progression. Moreover, subjects with RP performed worse than expected based on restricted fields alone.

Recent studies in the areas of vection,17 direction-of-heading detection,13,14 and postural control15,16 indicate that the central visual field can play a key role in self-motion perception. In fact, in subjects with normal vision whose vision was artificially restricted, Paulus et al16 found that a 30° stationary visual display in the central field stabilized better than a 30° stationary visual display in the peripheral field. This finding is not surprising when one considers that the visual functions that have been implicated in postural control, namely visual acuity16,17 and image-displacement thresholds,18 have their greatest sensitivity in the central visual field.19

If the central visual field does play a key role in postural control, then low-vision observers with compromised central visual fields should show a smaller visual contribution to postural stability than do subjects with normal vision.

Age-related macular degeneration (AMD) is a disease associated with compromised central visual fields. It is the leading cause of severe vision loss in people older than 50 years of age in the United States.20,21 Other visual deficits associated with AMD include reduced visual acuity22,23 and contrast sensitivity,24,25 decreased dark adaptation,26,27 and absolute sensitivity,28 as well as abnormalities in color vision29 and temporal function.30,31

In a recent survey conducted on 133 patients with AMD seen at The Lions Low Vision Center (Wilmer Institute, Baltimore, MD), only 10 (7.5%) subjects reported that they could not maintain balance because of vision-related problems. However, Elliott et al32 investigated postural control in subjects with AMD in a more objective manner. Their results showed that subjects with AMD have greater postural sway than do subjects with normal vision. However, their subjects with AMD had greater postural sway than did subjects with normal vision even when standing in the dark. The two subject groups apparently differed on more than vision factors. Unfortunately, the results were not analyzed in a way that permits a determination of the visual contribution to postural stabilization in the two groups.

The goal of this study was to determine whether people with central field loss from AMD showed less visual contribution to postural stability than did people with normal vision. To this end, we measured postural sway as subjects viewed a stationary display and as they stood in the dark. We adjusted for any difference in the groups’ magnitude of sway in the dark and determined whether there was a group difference in the magnitude of sway in the visual condition.

We also measured retinal image displacement thresholds in subjects with central field loss and in subjects with normal vision. Paulus et al18 postulated that the essential visual cue to lateral postural sway is sideways retinal target displacement, and that fore-aft sway changes image size and disparity through change of the eye-target distance. We hypothesize that the vertical retinal image displacement also may be a factor: As a person sways, his or her body pivots around a rotational point at the level of the ankle joint. Assuming that the head remains at a fixed angle with respect to the body, this pivoting movement introduces an angular retinal displacement over the same angle as that of the body pivot. This constitutes an additional stabilization feedback component over the two recognized by Paulus et al18 in the fore–aft body sway and could explain why their fore–aft results were more accurate than predicted. For this reason, as part of our study, angular retinal displacement thresholds were measured in a subset of the subjects.

METHODS

Subjects

Twenty people with normal vision and 19 people with central field loss served as subjects. The subjects with central field loss were diagnosed previously with AMD and were screened to exclude those who had other ocular pathologies. Subjects with a history of vestibular and/or somatosensory problems, as well as subjects requiring supportive devices for ambulation (e.g., support canes, walkers), were excluded from the study. There was no significant difference in age, height, or weight between the two groups (see Table 1 for a summary of the subject characteristics). All subjects wore their refractive corrections during the experiment. Informed consent was obtained from each subject after the nature and possible consequences of the study had been described. The research followed the tenets of the Declaration of Helsinki and was approved by the institutional human experimentation committee.

Apparatus to Measure Postural Sway

The EquiTest System (NeuroCom International, Clackamas, OR) was used to measure postural sway (Fig. 1). The apparatus consisted of a three-sided booth in which the subject normally stands facing the back. In our study, however, the subject faced the open side, toward a video display. The subject’s feet were placed approximately 15 cm apart, and the subject wore a harness attached to an overhead support as a safety precaution.

Anterior–posterior (AP) and lateral (L) postural sway were estimated from the output of four pressure transducers located within the corners of the platform on which the subject stood. The pressure transducers
TABLE 1. Summary Statistics of Subject Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Central Visual Field Loss</th>
<th>Normal Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>Range: 62 to 87</td>
<td>Range: 58 to 83</td>
</tr>
<tr>
<td></td>
<td>Mean (SD): 74.1 (6.0)</td>
<td>Mean (SD): 70.4 (6.7)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Range: 52.6 to 112.9</td>
<td>Range: 47.6 to 96.6</td>
</tr>
<tr>
<td></td>
<td>Mean (SD): 76.0 (16.1)</td>
<td>Mean (SD): 73.9 (12.9)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>Range: 1.57 to 1.85</td>
<td>Range: 1.52 to 1.85</td>
</tr>
<tr>
<td></td>
<td>Mean (SD): 1.70 (0.09)</td>
<td>Mean (SD): 1.71 (0.09)</td>
</tr>
<tr>
<td>Log MAR</td>
<td>Range: -0.02 to 1.32</td>
<td>Range: -0.19 to 0.18</td>
</tr>
<tr>
<td></td>
<td>Mean (SD): 0.80 (0.37)</td>
<td>Mean (SD): -0.03 (0.09)</td>
</tr>
<tr>
<td>Log CS</td>
<td>Range: 0.45 to 1.45</td>
<td>Range: 1.45 to 1.95</td>
</tr>
<tr>
<td></td>
<td>Mean (SD): 1.15 (0.26)</td>
<td>Mean (SD): 1.71 (0.15)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scotomas</th>
<th>Eye</th>
<th>Area (sq deg)</th>
<th></th>
<th>Area (sq deg)</th>
<th></th>
<th>Diameter (deg)</th>
<th></th>
<th>Diameter (deg)</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>OD</td>
<td>0 to 324</td>
<td></td>
<td>0 to 199</td>
<td></td>
<td>0 to 14.4</td>
<td></td>
<td>9.85 (5.6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>0 to 199</td>
<td></td>
<td>0 to 14.4</td>
<td></td>
<td>0 to 14.4</td>
<td></td>
<td>9.7 (4.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Binocular</td>
<td>0 to 180</td>
<td></td>
<td>49.6 (50.4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OD = right eye; OS = left eye.

OD = right eye; OS = left eye.

measure vertical forces applied to the forceplate. The total vertical force is the subject's weight, and it is the sum of the vertical forces measured by all four transducers. The total vertical force is calculated as

\[ F = \sum F_j \quad (1) \]

where \( F_j \) is the supporting force of the \( j \)th transducer.

The center position of the subject's vertical force was calculated along the anterior–posterior dimension as the difference between the front vertical forces and the back vertical forces divided by the total vertical force. The estimate is multiplied by a constant that represents one-half the distance between the front and back transducers. The AP center of vertical force is

\[ AP = \frac{\sum F_0 - \sum F_d}{F} \times d \quad (2) \]

where \( F_0 \) is the supporting force of the \( j \)th front transducers, \( F_d \) is the supporting force of the \( j \)th back transducers, and \( d \) is the distance between the force transducers and the left–right axis, which is 10.7 cm. The center position of the subject's vertical force was calculated along the lateral dimension in the same way, except that the left and right transducers substituted for the front and back. The current value of the instantaneous center position is passed through a second-order low-pass filter whose cut-off frequency is 0.89 Hz. In our study, the pressure transducers sampled at a rate of 100 samples/second over a 20-second time period.

When an observer stands on a stable support surface, the normal AP body sway results in inflection at the ankle joint, a reliable somatosensory cue to postural instability. In our study, subjects stood on a support surface that tilted in the direction of the subject's AP body sway. The EquiTest System used information about body sway to generate, by means of a servomotor, a rotation of the support surface around an axis collinear with the ankle joint, in proportion to the subject's AP sway. The somatosensory feedback was not nulled because of a small amount of time lag (50 msec to maximum velocity), but it was altered and, hence, less reliable.
In this way, we were able to measure postural sway under conditions in which somatosensory cues, such as changes in cutaneous and muscle pressure, muscle length, and joint angle, become less reliable in maintaining balance. A number of studies support the hypothesis that subjects are able to maintain their posture when there is reliable feedback from at least two of the three sensory systems: visual, somatosensory, and vestibular. Artificially reducing the reliability of the somatosensory feedback encourages the use of the sensory information from the visual and vestibular systems in the visual condition and the use of the vestibular information in the dark condition. The fact that we measured sway under conditions of reduced somatosensory feedback does not limit the generality of the results of this study. In everyday life, we frequently encounter situations of reduced or unreliable somatosensory feedback, e.g., walking on thick carpets, uneven surfaces, or slippery terrain. Furthermore, increased age is associated with declines in somatosensory function. Thus, we think the current findings will generalize to the everyday functioning of subjects with normal vision and subjects with CFL.

**Visual Stimuli Used in Postural Sway Experiments**

A video display was used to show computer-generated patterns of high-contrast, randomly positioned dots. The luminance of the dots was 82.5 cd/m², and the luminance of the background was 0.2 cd/m². The average number of visible dots was 400, and each dot subtended a visual angle of 12.4 min of arc horizontally and 10.3 min of arc vertically. The large number of high-contrast, stationary visual elements made the display an ideal visual stimulus for postural stabilization. The patterns (256 X 240 pixels) were generated using a MATROX graphics board controlled by an i386 laboratory computer, and they were displayed on a wide-screen, rear-projection television (model VS-409R; Mitsubishi, Rancho Dominguez, CA). The frame rate was 30 Hz. At the viewing distance of 80 cm, the display subtended a visual angle of 53° horizontally and 41° vertically. However, all subjects wore field-restricting goggles, which limited their field of view to 51° horizontally and 38° vertically. Because the goggles were made of dark material, there was no noticeable contrast difference between the edge of the screen in the darkened room and the rim of the goggles. Subjects were instructed to keep their gaze straight ahead so that the dots on the display screen would extend to the edge of the goggles.

**Procedure**

Sway was measured in all subjects under two conditions: Subjects either viewed the stationary-dot display, or they stood in the dark. Subjects were instructed to look straight ahead and to stand as still as possible with their arms down at their sides. In the visual condition, subjects binocularly viewed the visual pattern for 20 seconds in an otherwise darkened room. In the dark-environment condition, the display was turned off, and subjects stood in the dark for 20 seconds. Each subject first participated in three trials of the visual condition and then three trials of the dark condition.

**Analysis**

Sway magnitude was defined as the root-mean-square level of the AP or L center of pressure values sampled over the last 15 seconds after subtraction of any shift in DC level over that interval. This shift was computed through a least-square fit of a straight line to the signal. Figure 2 shows a graph of the AP center of pressure of a subject with normal vision plotted against time. The thick line represents the data from the visual condition, and the thin line represents the data from the dark condition. The sway magnitude for the visual condition was 0.41 cm, and the sway magnitude for the dark condition was 0.8 cm.

**Visual Function Measures**

Visual acuity was measured monocularly (better eye) and binocularly on all subjects with a Lighthouse ETDRS acuity chart transilluminated at 95 cd/m². Initial testing was at a distance of 3 m. If the subject was able to read at least 3 of 5 letters in the top line, acuity testing continued at this viewing distance. If not, the viewing distance was reduced to 2 m. If the subject was still unable to read three letters successfully, viewing distance was reduced to 1 m. The number of letters correctly read was converted to logMAR (the minimum angle of resolution) by subtracting (0.02 × number of letters) from a constant. The constant was 1.22 for tests conducted at a viewing distance...
of 3 m. For viewing distances of 2 m and 1 m, the constants were 1.4 and 1.7, respectively. Peak contrast sensitivity was measured monocularly (better eye) and binocularly on all subjects using the Pelli–Robson chart\textsuperscript{40} with overhead illumination (85 cd/m\textsuperscript{2}). Viewing distance was 1 m. Log peak contrast sensitivity was scored as the product of 0.05 and (number of letters - 3). Central visual fields (14.4° × 14.4°) were measured by static perimetry using the confocal scanning laser ophthalmoscope equipped with graphics capabilities.\textsuperscript{51} This system obtains retinal images continuously with an infrared laser. At the same time, graphics are scanned onto the retina with a modulated visible laser and are viewed by the subject. Subjects were instructed to fixate straight ahead at the fixation cross projected on the retina during visual field testing. Each eye was tested with a 10 min of arc target of retinal illuminance 8.6 × 10\textsuperscript{4} trolands, i.e., the laboratory's standard scanning laser ophthalmoscope perimetric test probe. A binocular visual field was constructed from the two monocular visual fields. Assuming that vergence is at the plane of the display, the binocular visual field is the common visual field area, and a binocular scotoma is the common scotomatosus area.

Angular Displacement Thresholds: Stimuli, Procedure, and Analysis

A person's ability to maintain stable posture has been shown to be degraded under stroboscopic illumination.\textsuperscript{16,42} This finding suggests that the detection of retinal image motion plays a critical role in the visual control of posture. To determine whether retinal displacement thresholds are associated with the magnitude of visual stabilization, displacement thresholds, $d_{\text{min}}$, were measured monocularly and binocularly on a subset of each subject group (12 subjects with CFL and 16 subjects with normal vision). Random-dot patterns were generated by an IMAGRAPH high-resolution graphics display board (1024 × 1024 × 8 bits) controlled by an i386 laboratory computer. The patterns were displayed on a high-resolution CRT monitor (Ikegami Electronics, Maywood, NJ). The display was refreshed at a rate of 60 Hz without interlace. A display sequence consisted of seven images, each containing 50 random dots and displayed for 133.3 msec (total duration, 933 msec). The configuration of the dots in each image was the same but shifted vertically (up or down, randomly determined) within a spatially fixed window by a constant amount across the frames (see Fig. 3). Dots lost at the edge of the window wrapped around to appear within the opposite boundary. Viewing distance was 127 cm or 250 cm, depending on the subject's visual acuity. Viewing distance was increased for subjects with visual acuities better than 20/30 to generate angular displacements small enough to measure $d_{\text{min}}$. The size of the display was reduced appropriately for the closer viewing distance to maintain a window size of 6° × 6°. At a viewing distance of 250 cm, each pixel was 0.35 min of arc, and, at a viewing distance of 127 cm, each pixel was 0.69 min of arc. On each trial, the subject viewed a single motion sequence. The subject's task was to determine which of the two directions (up or down) the pattern moved. Displacement magnitude was varied with a two down–one up staircase procedure to determine $d_{\text{min}}$; displacement magnitude decreased after two consecutive correct responses, and it increased after a single incorrect response. Testing was terminated after 12 reversals, and for each subject, the proportion of correct responses per displacement magnitude was calculated. A Weibull function (equation 3) was fitted to the proportion-correct distribution using a maximum likelihood procedure with a simplex maximizing routine. The parameter $\beta$ specifies the slope of the psychometric function. The parameter $\alpha$ specifies the displacement magnitude, where performance is at 82% correct. This displacement magnitude was arbitrarily chosen to be the displacement threshold, $d_{\text{min}}$.

\begin{equation}
    f(x) = 1 - 0.5 \times \exp\left[-\left(x/\alpha^\beta\right)\right]
\end{equation}

RESULTS

For each subject and for each condition, sway was measured three times. To determine whether there
was a learning effect across trials, we ran a paired \( t \)-test on the sway values obtained in trial 1 and in trial 3 using data from both conditions (visual and dark) and sway directions (AP and L). We found no evidence of a learning effect; \( t(155) = -0.66 \) (ns).

For each subject and condition, a mean root-mean-square was computed. The mean for the dark condition will be referred to as \( \text{sway}_D \), and the mean for the visual condition will be referred to as \( \text{sway}_V \).

For the subjects with normal vision, the mean AP \( \text{sway}_V \) was 0.44 cm (SD = 0.13 cm), and for the subjects with CFL, the mean was 0.55 cm (SD = 0.16 cm). We ran an analysis of covariance, to compare the means of the AP \( \text{sway}_V \) distributions of the CFL and groups with normal vision while adjusting for any group difference in \( \text{sway}_D \). \( \text{sway}_D \) and age served as the covariate factors. Height and weight were not correlated with \( \text{sway}_V \).† The results showed that the CFL group had significantly larger \( \text{sway}_V \) values than did the subjects with normal vision (\( F = 6.71, P < 0.02 \)).

The mean of AP \( \text{sway}_D \) of the subjects with normal vision was 0.74 cm (SD = 0.23 cm), and for the subjects with CFL, the mean was 0.78 cm (SD = 0.27 cm). Although this value is again larger for the CFL subject group, the results of a \( t \)-test revealed that the \( \text{sway}_D \) difference between the two subject groups was not statistically significant, \( t(37) = 0.49 \), unlike the findings in the Elliott et al. 32 study. The magnitude of sway in the dark was greater than the magnitude of the sway in the visual condition for both subject groups, but the decrease of sway magnitude in the visual condition was larger for the normally sighted subjects than for the subjects with CFL (41% and 29%, respectively).

The mean of the L \( \text{sway}_V \) of the subjects with normal vision was 0.15 cm (SD = 0.07 cm), and for the subjects with CFL, it was 0.22 cm (SD = 0.15 cm). To compare the distributions of L \( \text{sway}_V \) between the groups with CFL and normal vision, we ran an analysis of covariance, with L \( \text{sway}_D \) as the covariate.§ The results showed no significant difference between the means of the two groups; \( F = 1.1 \). Furthermore, in both groups, there was little difference between L \( \text{sway}_V \) and L \( \text{sway}_D \). The mean of the subjects with normal vision L \( \text{sway}_D \) was 0.20 cm (SD = 0.11 cm) and, for the subjects with CFL, it was 0.27 cm (SD = 0.16 cm). In both subject groups, the reduction in sway from visual stimuli was 25% or less.

The magnitude of the visual contribution to stabilization was computed as the ratio of AP \( \text{sway}_D \) to AP \( \text{sway}_V \), and this visual stabilization index was used to evaluate the effects of the visual-function measures. An index of 1 indicates no visual contribution to postural stabilization. Values greater than 1 indicate a visual stabilizing effect.

The mean of visual stabilization of the subjects with normal vision was 1.73 (SD = 0.45), and for the subjects with CFL, it was 1.44 (SD = 0.36). Subjects with CFL showed a smaller visual contribution to posture stabilization than subjects with normal vision; \( t(37) = -2.2, P < 0.04 \).

### Relationship to Visual Function Measures

Regression analyses were performed to determine how well the magnitude of the visual stabilization index was predicted from each of the two monocular visual field measures: scotomatous area within the central visual field \((14.4° \times 14.4°)\) and diameter of the central field scotomas. Results showed that neither of the two monocular measures was associated significantly with the visual stabilization magnitude (see Table 2 for a report of the coefficients of determination). Furthermore, subjects with CFL who had a scotoma somewhere within the central 5° of only one eye (monocular scotoma) exhibited the same magnitude of visual stabilization as did subjects with CFL who had no scotomas within the central 5° of either eye.

However, there was a significant difference between the magnitudes of the visual stabilization of the subjects with CFL who had a binocular scotoma somewhere within the central 5° and the subjects with CFL who did not. Subjects who had a binocular scotoma somewhere within the central 5° exhibited, on average, lower visual stabilization than did subjects with CFL who did not; \( t(17) = 2.49, P < 0.02 \).

Figure 4 is a scatterplot showing the distributions of the magnitude of visual stabilization for the subjects with CFL who did and did not have a binocular scotoma within the central 5°. The solid diamonds represent the means of the two distributions. The dashed line marks a visual stabilization index of 1, indicating no visual contribution to postural stabilization. Note the shift in visual stabilization magnitudes toward lower levels for the subjects who had a binocular scotoma.

Under conditions of reduced somatosensory information, the amount that a person sways when his or her eyes are open has been shown to covary with measures of visual acuity 17 and contrast sensitivity in older people. 5,17,45 In our study, people with normal vision had better visual acuity, indexed by logMAR, and contrast sensitivity, indexed by the log of the peak contrast sensitivity (see Table 1). To determine whether logMAR, log peak contrast sensitivity, or both affected visual stabilization significantly and appreciably in subjects with CFL, we incorporated these vari-

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† Correlation coefficients for \( \text{sway}_D \) and nonvisual subject characteristics are as follows: \( \text{sway}_D \), \( r = 0.60, P < 0.0001 \); age, \( r = 0.52, P < 0.05 \); height, \( r = 0.05, \) ns; weight, \( r = -0.02, \) ns.

§ Correlation coefficients for L \( \text{sway}_V \) and nonvisual subject characteristics are as follows: L \( \text{sway}_V \), \( r = 0.64, P < 0.0001 \); age, \( r = 0.19, \) ns; height, \( r = 0.08, \) ns; weight, \( r = 0.29, \) ns.
TABLE 2. Coefficients of Determination for the Visual Stabilization Index

<table>
<thead>
<tr>
<th>Visual Measure</th>
<th>All Subjects With CFL</th>
<th>All Subjects With CFL Tested for dmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scotomas</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Area: OD</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Area: OS</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Diameter: OD</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Binocular-scot factor</td>
<td>0.27*</td>
<td>0.22</td>
</tr>
<tr>
<td>LogMAR</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Binocular logMAR</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Log CS</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Binocular log CS</td>
<td>0.01</td>
<td>0.45*</td>
</tr>
</tbody>
</table>

* $P < 0.025$.
CFL = central visual field loss; OD = right eye; OS = left eye.

When we added the binocular-scotoma factor to $d_{\text{min}}$, the coefficient of determination did not change. Not surprisingly, this demonstrates that there is an interaction between the binocular-scotoma factor and $d_{\text{min}}$. The subjects with CFL who had a binocular scotoma within the central 5° had significantly higher $d_{\text{min}}$ values than the subjects with CFL who did not have a binocular central scotoma; $t(9) = 2.94, P < 0.02$.

The relationship between visual stabilization magnitude and $d_{\text{min}}$ is depicted in Figure 5 for the subjects with CFL. (Note that only 11 subjects with CFL have a $d_{\text{min}}$ value. $d_{\text{min}}$ for one CFL subject could not be computed because of the nonmonotonicity of percent correct to displacement magnitude.) The x-axis is the magnitude of image displacement per frame. The closed circles represent the CFL data, and the open diamond represents the mean visual stabilization magni-
nitude of the subjects with normal vision plotted at the mean $d_{\text{min}}$ of the subjects with normal vision. The line is the best-fitted linear regression of the CFL data. The regression coefficient of $d_{\text{min}}$ is $-0.17$, and it is statistically significant at the 0.025 level.

**DISCUSSION**

In our study, for the subjects with normal vision, visual information reduced postural sway, on average, by 41%. The average reduction in sway for the subjects with CFL was 29%. Some subjects with CFL exhibited sway reductions comparable to the mean of the subjects with normal vision, whereas some exhibited sway reductions significantly less than the normal mean. One subject with CFL actually showed increased sway in the visual condition (visual stabilization index <1).

The results of a multiple regression analysis showed that among the visual function measures—logMAR, log contrast sensitivity, central visual field parameters, and $d_{\text{min}}$—the binocular–scotoma factor and $d_{\text{min}}$ were the only variables that significantly affected the magnitude of visual stabilization. Of those two, $d_{\text{min}}$ accounted for more of the variation in the magnitude of visual stabilization. The relationship between $d_{\text{min}}$ and the visual stabilization magnitude strongly suggests that the angular displacement on the retina is a contributing factor in AP sway, contrary to the analysis of Paulus et al. This additional stabilization feedback component over the two recognized by Paulus et al in the fore-aft body sway would help to explain why their fore-aft results were more accurate than predicted by their model.

Subjects who had close-to-normal $d_{\text{min}}$ values exhibited normal visual stabilization. As $d_{\text{min}}$ increased, visual stabilization magnitude decreased in a linear manner. At a $d_{\text{min}}$ value approximately four times the distribution mean of normal vision, 3 of 5 subjects with CFL showed no visual contribution to posture stabilization (Fig. 5). One possible interpretation of this finding is that the image displacements produced from small body oscillations were undetectable by the subjects with elevated displacement thresholds. Consequently, a greater sway path was necessary to generate image displacements large enough to be detected by these subjects.

Paulus et al suggested that as the reliability of visual information becomes compromised, there is an enhancement of the contribution of the remaining unaffected systems—somatosensory, vestibular, or both. If this were true, we would expect sway$_0$ to be lower for the subjects with CFL than for the subjects with normal vision. Our results do not point in this direction; there was no significant difference between the means of the sway$_0$ distributions for the two subject groups.

The magnitude of lateral sway, also was not different for the two subject groups. This finding was unexpected given the previous report on the fovea’s powerful contribution to lateral stabilization. It had been shown that only one light-emitting diode fixated in darkness by observers with normal vision is sufficient to produce lateral stabilization of posture. Our results showed little reduction in lateral sway with visual information for either subject group. Subjects in both groups (CFL and normal vision) showed fairly stable lateral position even in the dark. We attribute this to the fact that somatosensory information was not decoupled in the lateral dimension as it was in the AP dimension. Thus, the somatosensory information along this dimension may have been sufficient to keep sway to a minimum.

In conclusion, subjects with central field loss show a smaller visual contribution to postural stabilization than do subjects with normal vision. Whereas the presence of a binocular scotoma somewhere within the central 5° significantly affects the magnitude of visual stabilization, the coefficient of determination for the magnitude of visual stabilization is higher for $d_{\text{min}}$.

**Key Words**

central field loss, displacement threshold, low vision, macular degeneration, postural stability

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**References**


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