Effect of visual distortion on postural balance in a full immersion stereoscopic environment

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ABSTRACT

This study attempted to determine the influence of non-linear visual movements on our capacity to maintain postural control. An 8x8x8 foot CAVE immersive virtual environment was used. Body sway recordings were obtained for both head and lower back (lumbar 2-3) positions. The subjects were presented with visual stimuli for periods of 62.5 seconds. Subjects were asked to stand still on one foot while viewing stimuli consisting of multiplied sine waves generating movement undulation of a textured surface (waves moving in checkerboard pattern). Three wave amplitudes were tested: 4 feet, 2 feet, and 1 foot. Two viewing conditions were also used; observers looking at 36 inches in front of their feet; observers looking at a distance near the horizon. The results were compiled using an instability index and the data showed a profound and consistent effect of visual disturbances on postural balance in particular for the x (side-to-side) movement. We have demonstrated that non-linear visual distortions similar to those generated by progressive ophthalmic lenses of the kind used for presbyopia corrections, can generate significant postural instability. This instability is particularly evident for the side-to-side body movement and is most evident for the near viewing condition.

Keywords: Progressive lens, perceptual sway, posture, visual distortion, presbyopia, immersive display, virtual reality.

1. INTRODUCTION

As we move about in the environment we are often faced with a number of visual distortions caused by different refractive gradients yet we appear to compensate for them in an effortless manner. However, there are distortions that must influence our behaviors in a significant manner. The most common cause of visual distortions that an observer is faced with comes from ametropia correction with ophthalmic lenses. While corrections for myopia or hyperopia should yield symmetric distortions if the lenses are appropriately adjusted, a special case of non-linear distortion is present when observers use bifocal or progressive lenses that correct both for ametropia and presbyopia. The question is how much do these visual distortions influence our behaviors such as reaching, walking or posture control? The later is the focus of the present study.

1.1 Presbyopia and progressive lenses

The aging demographics clearly indicate that the mean age of the North American population is increasing rapidly. Presbyopia is a well known consequence of the aging human eye. Almost 100% of the population will be faced with this problem in the 50s and the majority of humans will show signs of presbyopia in the 40s. Because near vision is increasingly important in the work environment and for leisure, an adequate correction strategy for this problem becomes a primordial issue for the aging population.

The most ancient, and still the most efficient, correction for presbyopia remains the ophthalmic lens. Although there have been recent advances in surgical techniques, the short term benefits are still uncertain and nothing is known about the long term consequences. One thing is certain, surgical procedures cannot change the properties of optical physics and simultaneously resolve the problem of near and distance correction, which requires and adaptive system.

No matter which type of correction is used to minimize the impact of presbyopia, one is left with the same basic issues. What does the wearer see? What is the minimal correction required and at what level does the wearer become incapable to tolerate a variable refraction? Can we predict the outcome of a wearer's visual performance by the type of correction required or by demographic characteristics such as the wearer's age, optical parameters of the eye,

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and experience with lens wear? How much adaptation does or does not take place? Does age interact with adaptation? What are the situations that potentially place the wearer at risk of injury or inconveniences?

1.2. Basic principles of geometrical optical distortion

Before elaborating on the experimental procedures that are planed for the study we will first introduce some basic principles of optical distortions as it relates to a progressive additional lens.

To illustrate this point we can start with simple examples of optical distortions produced by positive (hyperopic correction) or negative (myopic correction) lenses. The model chosen to make this point is based on the Le Grand-Fry approach[1,2,3]. These optical models have the advantage of establishing possible distortions produced by ophthalmic lenses from a wearer's perspective[4].

Figure 1 demonstrates the classic barrel and pincushion distortions produced by negative and positive power lenses that correct for myopia and hyperopia respectively. For a more thorough discussion on how such distortion grids are generated from a ray-tracing model see Faubert[5]. The light grey grid shown in the background represents the standard visual pattern prior to viewing through lenses and the dark grid represents the model results after tracing the rays through the ophthalmic correction lens. In this case the line of sight (fixation point) is positioned in the center of the reference grid. Figure 2 demonstrates the effect of a typical progressive lens design on an image. Because the progressive change in refractive power is in the lower visual field (below fixation point) the line of sight is positioned at the top of the grid to illustrate such effects. Figure 3 demonstrates further what happens to an image when fixation is maintained but the head is moved left or right. The resulting image is a non-bilaterally symmetric image in reference to the vertical midline. The potential complications arising from the use of a progressive lens comes from the interaction of two factors that vary simultaneously. As the image moves away from the central axis of the lens, there is both a magnification effect resulting from the increased power gradient of the progressive lens and, as a consequence, there is also an increase in distortion of the perceived image. If the head is in motion while the eyes remained fixated on the same point, one can perceive strong changes in the spatial-temporal components of the image. In other words, the motion parallax and optic flow components of a scene that is perceived under natural circumstances is dramatically changed by the refractive optics. Observers report sway sensations when moving their heads and fixating a single point, or when the eyes move behind the lens while the head is maintained in one position. The perception of sway has been identified as the single most important factor that may cause difficulties in adaptation when wearing presbyopic correction lenses[6]. The specific question of the present study is to determine whether visual sway can influence our capacity to maintain postural balance.

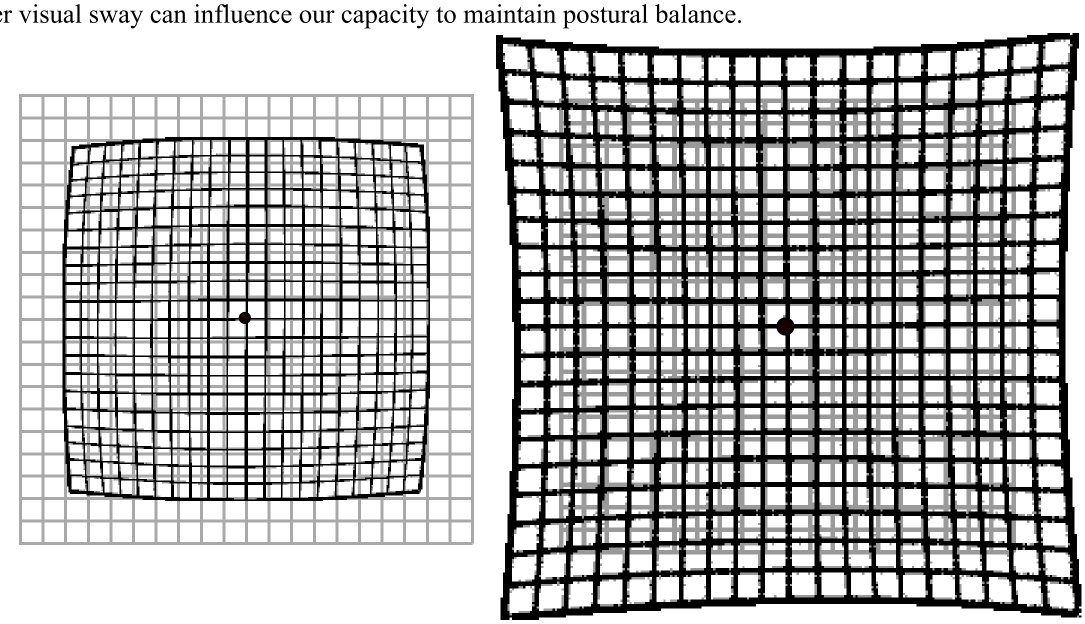

Figure 1. The left image reproduces the non-distorted grid (light gray) superimposed by a front view projection of the distorted image from a minus spherical lens (black lines) and the right image shows the same standard grid superimposed with a model projection from a positive spherical lens. The black dot in the center of the image shows the fixation point. Adapted from Faubert[5].

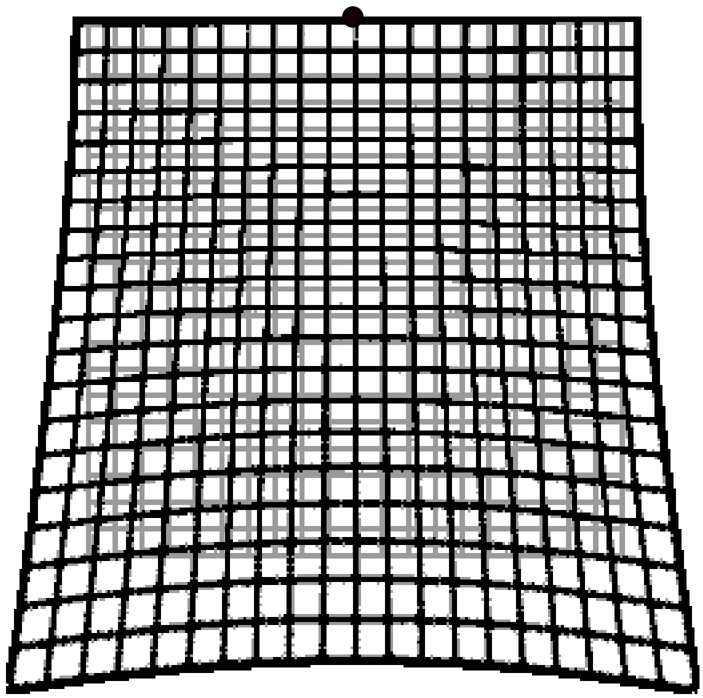

Figure 2. Standard grid superimposed with a model projection calculated for a typical progression addition lens. The black dot at the top of the image grid shows the fixation point and the reference axis of the lens. Notice that the distortion from a viewer's perspective induced by the progressive correction is in the lower visual field area and is non-uniform as a function of eccentricity. Adapted from Faubert[5].

1.3 Influence of visual perception on postural balance

Postural control is influenced by visual information. Studies have shown that even a simple visual defocus will increase instability if input from other sensory modalities were disrupted[7]. Some studies explicitly examined the effect of sway on postural balance. For example, Kay and Warren[8] studied observers for posture and gait coupling changes as a function of optic flow where sinusoidal oscillations were introduced. Although studies such as these give us some notions as to what visual information may produce postural imbalance and the coupling of posture and gait, we cannot directly extrapolate to our specific interest of induced lens distortions on posture. The reason is that the sway induced in their patterns (lateral oscillations of the visual display) does not mimic the sway observed through progressive lenses such as presented above. In our case we want to introduce simultaneous lateral displacement and image magnification, which generates changes in perceived depth of the images on the floor for instance.

1.4 Present study

In our study we used new stimuli that more closely mimics possible distortions from progressive additional lenses. The stimuli consisted of multiplied sine wave functions that generate both lateral movements and depth information. By manipulation the phase of the functions in regards to the standing position of the observer, we were able to simulate visual distortions that would be generated by different viewing conditions through progressive lenses. We manipulated the amplitude of the sine waves, which is analogous to changing the amplitude of head-eye movements through lenses while maintaining the base drift frequency of the sinusoids constant. Our hypothesis was that postural instability would increase as a function of the wave amplitudes (changes in perceived depth of the waves). This would imply that non-linear distortions could generate postural instability under certain conditions. Alternatively, if wave amplitude did not generate greater instability, we would have to conclude that non-linear distortions from progressive lenses did not produce postural instability in our conditions.

2. METHODS

2.1 Subjects

Five emmetrope subjects with 20/20 (6/6) vision were tested for the different experimental conditions.

2.2 Apparatus

An 8x8x8 feet CAVE environment (Fakespace) was used which included three walls and a floor[9]. The resolution of each surface image was 1280x1024 pixels generated by Marquee Ultra 8500 projectors. The CAVE was under the computer control of an SGI ONYX 3200 (two Infinite Reality 2 graphics cards). The CAVE was equipped with a magnetic motion tracker system (Flock-of-Birds).

2.3 Stimuli

The texture of the virtual floor was composed of a black and white checkerboard pattern with each square being 1x1 foot in size. The virtual display size was 100x100 feet and the subject was positioned at the horizontal midpoint and 5 feet from the beginning of the display (see Figure 3).

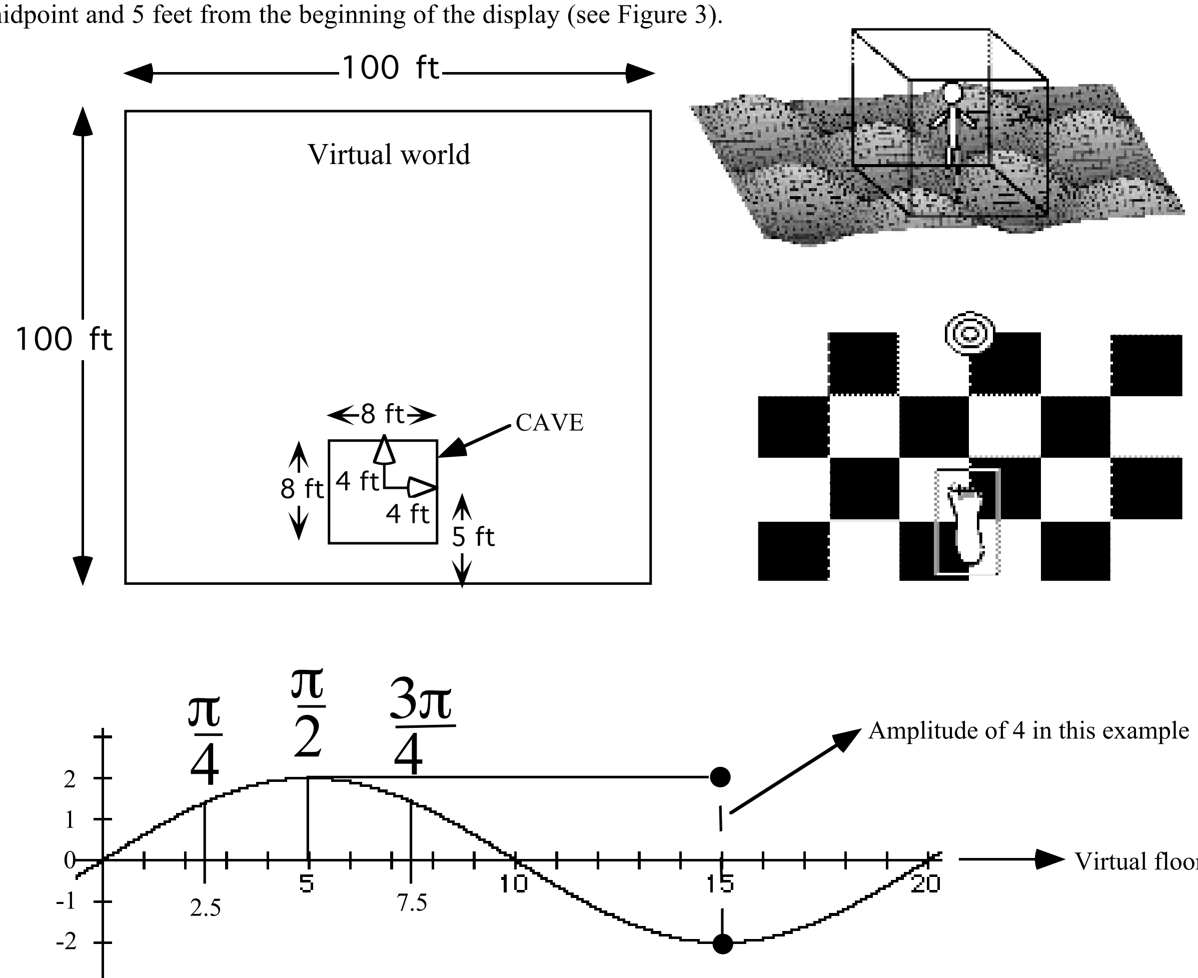

Figure 2. Top left figure demonstrates the extent of the virtual world and how the CAVE and the observer were positioned relative to it. The subject was positioned in the center of the CAVE. The virtual world (checkerboard pattern) started 5 feet behind the observer. Top right image illustrates a segment of the virtual world in 3D as seen by the observer when the amplitude condition was greater than 0. The right image in the center demonstrates the near fixation point of the observer relative to standing position. The bottom figure shows a 2D profile of the waveform. The different phase positions of the waves are shown where 0 position corresponds to the nodal point and pi/2 is the peak and trough of the wave. The impression for the observer under this condition is of a roller coaster ride while true sway is induced at the 0 phase condition.

The motion stimuli distortions were obtained from multiplied sine waves formally defined by:

$$z = \frac{Amp}{2}\sin\left(2\pi F_{sx} x + P_x\right)\sin\left(2\pi F_{sy}\left(y + t F_{ty}\right)\right)$$

where:

Amp = 0, 1, 2, 4 feet, F_{sx} = .05 cycles/foot, F_{sy} = .05 cycles/foot, P_x = 0, $\pi/4$, $\pi/2$, $3\pi/4$, F_{ty} = -8 feet/sec, t = time in seconds.

As a consequence the x and y spatial frequencies of the modulated distortions were 0.05 cycles / foot and the drift frequency was 2.5 seconds per cycle or 0.4 Hz on the y-axis (waves moved towards the observer). Four different wave amplitudes were generated (0, 1, 2 and 4 feet) as measured from the minimum and maximum distance relative to the virtual floor (see Figure 3). The 0 amplitude condition (control) produces no movement (static checkerboard). Different stimuli for each of four phase conditions relative to the observer were also generated: 0 (nodal point of the multiplied sinusoids), $\pi/4$, $\pi/2$, $3\pi/4$ (see Figure 3).

2.4 Motion Capture

Body posture was registered with motion sensors at the head (stereogoggles) and lower back (lumbar 2,3) positions. Sampling frequency was 60 Hz. Given that each test drive was 62,5 seconds and the first 2.5 seconds were not used, we registered a total of 3601 positions (3600 plus final position) for each run. This translates to 150 body position measurements per wave cycle. Prior to the experiment, a precise calibration of the motion sensor system was performed by displacing the sensors every foot in x, y, and z coordinates and registering the recorded position. A calibration function was implemented to correct for any mismatch between real sensor position and recorded position.

2.5 Procedure

In addition to the four amplitude and four phase stimuli conditions, we had two fixation conditions (see Figure 3). In one condition the observer had to fixate at three feet in front of the vertical midpoint of the body (i.e. three squares ahead) and in another condition the observer had to fixate at the horizon. In both cases fixation was always straight ahead (on the y-axis). The observers were asked to stand on one leg with their shoes off. Each leg was tested for all parameter conditions. In total, therefore, observers underwent 64 different conditions (4 amplitudes by 4 phases by 2 viewing conditions by 2 standing positions). In a given testing run, subjects positioned themselves at the center of the CAVE with their shoes off. The flat checkerboard pattern was already present and the subject was asked to fixate with their head positioned straight ahead either at the beginning of the third square (near fixation condition) or at the horizon (far fixation condition). Then the subject was asked to stand on one foot and then the testing run started. Testing conditions were ordered in a speudorandom sequence for each observer.

2.6 Data reduction

2.6.1 Instability Index (II):

The data were analyzed in different ways. Our first measure of interest corresponds to an instability index (*II*), which was calculated by the following formula:

$$II = \sqrt{\frac{\sum_{i=1}^{3600} s_i^2}{3600}}$$

$s_i = (p_i - p_{i-1})$ x 60 Hz, where s_i stands for the speed of displacement estimate in feet per second at the i^th recording where i = 1, 2, … , 3600.

2.6.2 Cycle-dependent Instability Index (CII):

The second analysis corresponds to the cycle-dependent instability index (*CII*) or the average speed (24 sampled cycles) for a given sampling position (150 positions) in wave cycle (c_i) and can be calculated as:

$$c_i = \sum_{j=0}^{23} s_{24j+i} \text{ where i = 1, 2, …, 150}$$

This second analysis demonstrates how the subjects' body movements corresponded to the phase of the sinusoidal waveforms.

3. RESULTS & DISCUSSION

3.1 Postural instability as a function of wave amplitude

Figure 4 shows the group mean *II* as a function of wave amplitude for the two different detector positions pooled for viewing conditions. What is obvious from the results is that both sensor position measures increase as a function of wave amplitude with the head movement data showing a steeper slope. This result was expected, as the body should work as an inverse pendulum in regards to maintaining posture. Because of space limitation we have pooled the data to look at issues such as axes of movement and fixation conditions.

Figure 5 shows the main effect of fixation. When observers were looking at three feet from their stance, body posture was more stable for the control condition than when they were fixating at distance. The trend reversed with increasing wave amplitude showing dramatic postural instability at the largest amplitude for the near viewing condition. This is interesting for several reasons. When maintaining postural balance in ecological environments we observe the world from different viewpoints. If we are walking about and looking at a distance, the postural instability would be less affected by distortions from progressive ophthalmic lenses, which is most obvious in the lower visual field. Our near viewing task, however, resembles many viewing conditions encountered in daily living tasks. For instance, when an observer addresses a staircase or escalator, moves on or off sidewalks or in and out of vehicles, he/she will inevitably look down just ahead of the stance position. Another example is when we play golf. The ball is positioned at a similar distance to our near viewing condition in the experiment. When pulling the golf club back, and then swinging thru, fixation must be maintained on the ball for a successful hit. The distortion induced in this case is analogous to our near viewing condition. It is clear that wearing progressive lenses in this context will generate postural instability as demonstrated from our results. This is probably why golfing is the major complaint of golfers in regards to wearing progressive lenses.

A breakdown of the different movement axis data (x, y, z) as a function of wave amplitude is shown in Figure 6. What is clear from the Figure 6 is that data for all axes of movement increase with augmenting wave amplitude. The x-axis representing lateral movement shows by far the most postural instability as a function of wave amplitude. As our primary interest is the consequence of perceptual sway on postural balance, we can conclude that distortion induces significant left-right body movement. Again, this is of critical interest in daily tasks as a progressive lens wearer may have more difficulties in addressing escalators or walking thru narrow openings.

Finally, we show that the phase of the waves in regards to the observer have different effects on postural instability as indicated in Figure 7. Although in our experimental conditions the 0 phase condition is the one that best simulates lens-induced distortions, an observer may be faced with a multitude of perceptual distortions analogous to our other conditions (ex. during skiing). The data show that at our largest amplitude condition, the non-zero phase conditions will generate greater postural instability.

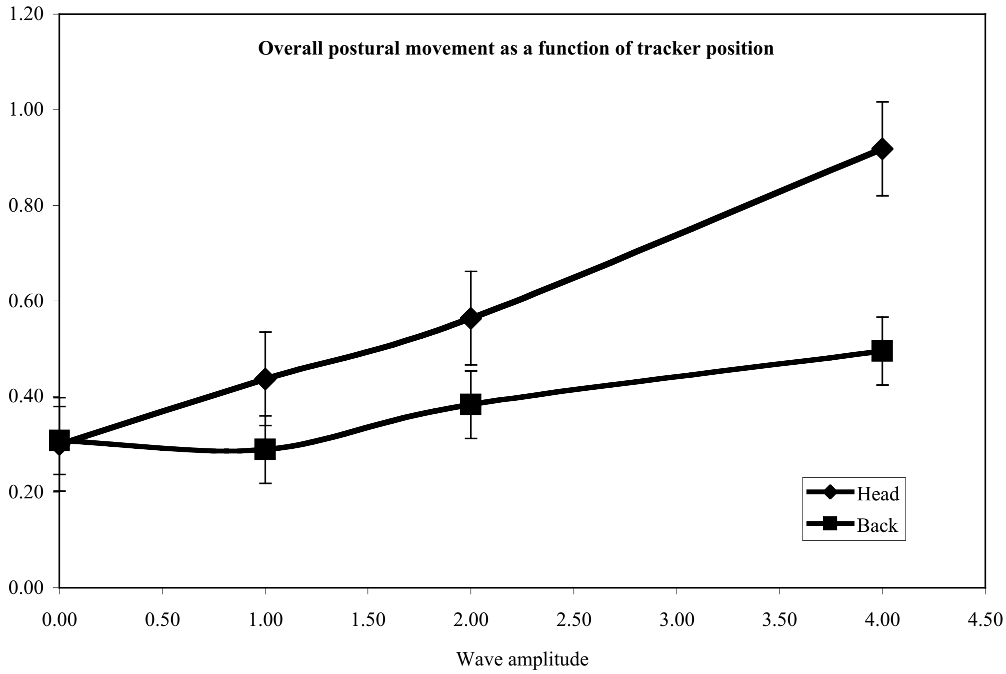

Figure 4. Postural movement (*II*) as a function of wave amplitude for data collected at two sensor positions (head and lower back). Error bars represent the average standard error of the mean (n=5).

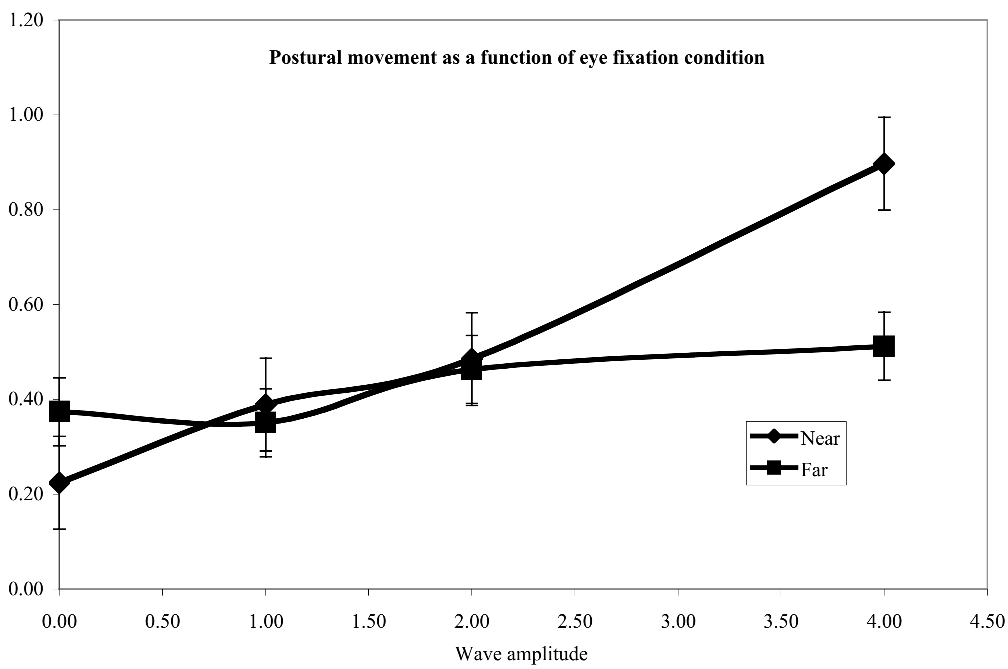

Figure 5. Postural movement (*II*) as a function of wave amplitude for data collected for the near and far fixation conditions. Error bars represent the average standard error of the mean (n=5).

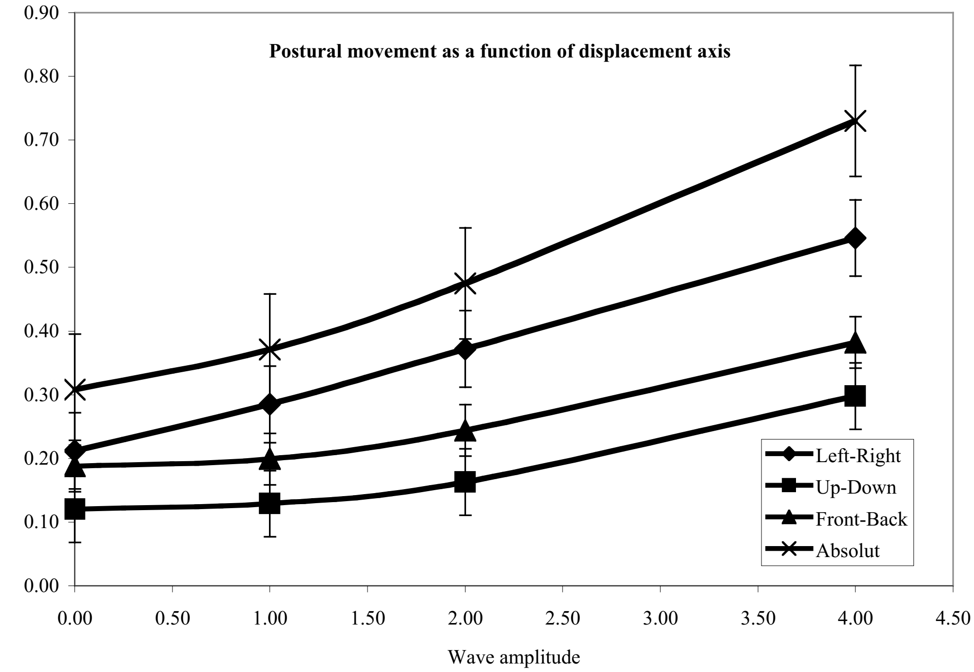

Figure 6. Postural movement (*II*) as a function of wave amplitude for the different types of movements on the x (left-right), y (front-back) and z (up-down) axes. Error bars represent the average standard error of the mean (n=5).

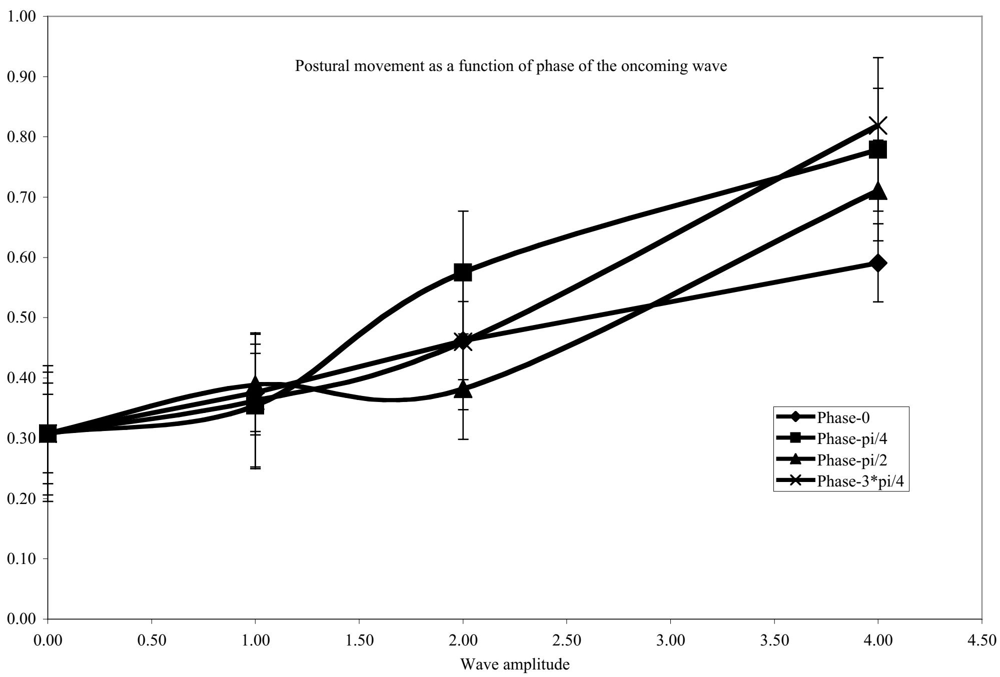

Figure 7. Postural movement (*II*) as a function of wave amplitude for the different wave phase conditions as illustrated in Figure 3 (0, πι/4, πι /2, 3 πι /4). Error bars represent the average standard error of the mean (n=5).

3.2 Postural instability as a function of wave position

As mentioned above, a second approach for data analysis was implemented in an attempt to understand the role of wave cycle on postural control. As the majority of postural imbalance is related to the lateral body motion (x) we present only these data in the figures below. Given that the motion of interest to us corresponds to sway motion, we only report the CII analysis for the 0 phase condition. Figure 8 shows the data for the near fixation condition and Figure 9 for the far viewing condition. The negative values represent a leaning slope of left to right and a positive value corresponds to a leaning slope of right to left.

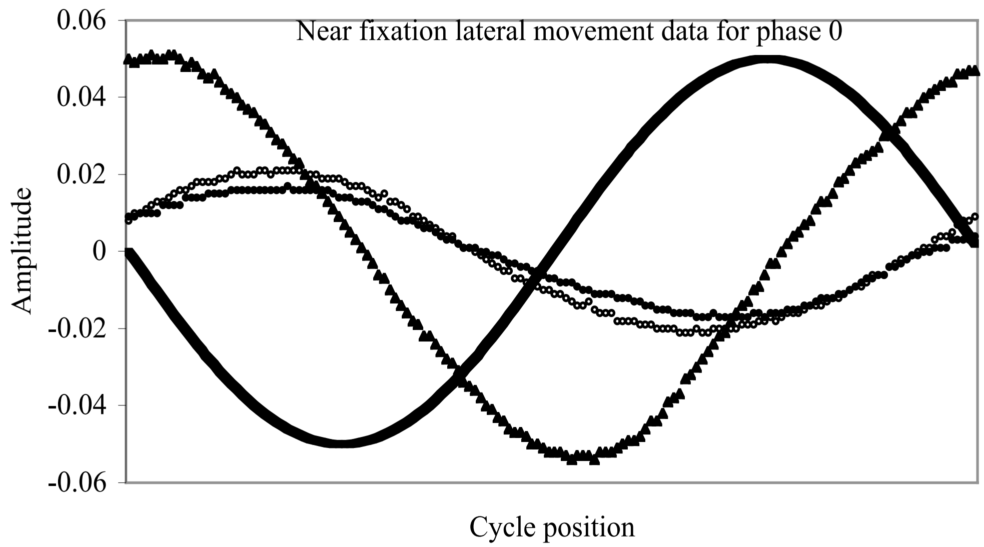

Figure 8. Cycle-dependent postural movement (*CII*) as a function of cycle position for the three non-zero amplitude and near viewing conditions. The zero amplitude condition is not shown as it essentially generates a straight line relative to the 0 value. The solid line represents the visual display as a function of stance position.

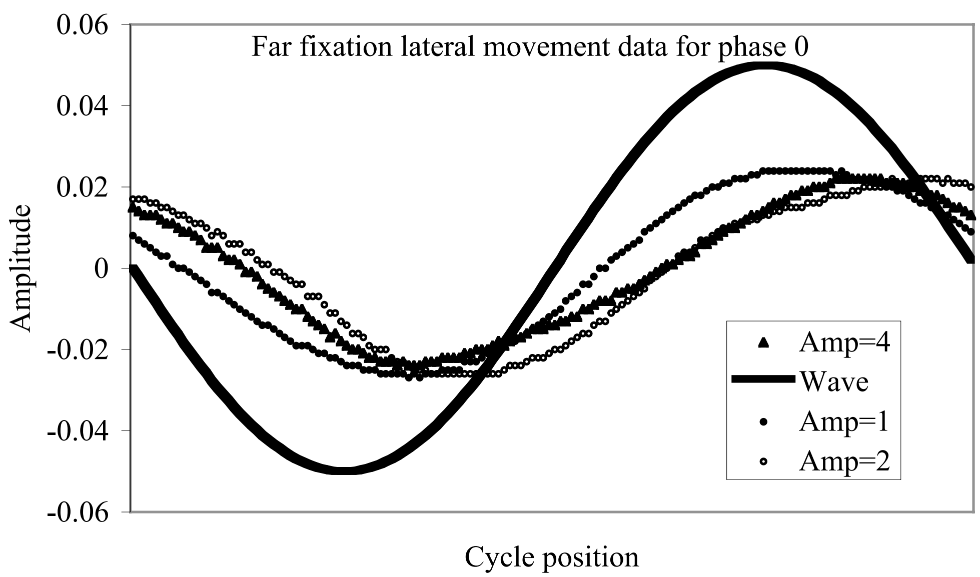

Figure 9. Cycle-dependent postural movement (*CII*) as a function of cycle position for the three non-zero amplitude and far viewing conditions. The zero amplitude condition is not shown as it essentially generates a straight line relative to the 0 value. The solid line represents the visual display as a function of stance position.

As can be seen from Figure 8, the observers generally adapt a counterphase strategy to maintain postural balance in the near viewing condition. These results demonstrate two things. First of all, it shows that the visual input has a strong influence on postural balance control and, secondly, it demonstrates that the observers use a compensatory strategy in order to maintain balance. In this case, it is obvious that the subjects leaned in the opposite direction of the visual stimulus at the level of stance position. This is evidence that visual input is a very strong cue used by the brain to maintain postural control.

Interestingly, Figure 9 shows that we use a totally different strategy when fixating at far. In this case the body tends to lean in the same direction as the wave and this corresponds more to a reactive (passive) effect to the visual input on postural balance. In both near and far viewing conditions, we show that visual input has a profound influence on posture. However, we can assume based on the data that programming of postural stance based on visual information is primarily active for near viewing conditions.

In general these data determine that visual input has a strong influence on postural control and the particular viewing conditions are of critical importance in the strategies that are used by the visual-motor system in order to maintain posture. This initial study has determined that the CAVE environment is well suited to understand the intricate impact that visual perception may have on our ability to keep stable. Furthermore, it raises several issues that warrant further experimentation. For instance, we used a particularly challenging stance task. The question remains whether the visual input will have the same influence when other stance positions are used such as standing on foam with both legs or in tandem (one foot in front of the other). Issues such as aging effect are also of interest. Given that presbyopes are generally from the older population and that this population already presents signs of postural instability[10] and reduced perceptual performance[11] relative to younger observers, it will be interesting to determine the influence of perceptual sway in the older population. Finally, optical modeling of progressive lens-induced distortions under different viewing conditions will be required in an attempt to predict and associate lens distortions to postural imbalance that could be predicted by our results.

Acknowledgements: This work was supported by the NSERC-Essilor Industrial Research Chair on Presbyopia and Visual Perception and by a Canadian Foundation for Innovation infrastructure grant.

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