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Balance Performance Measurment in a Phase Shifted Feedback Environment

Craig Alan Hoovler
Virginia Commonwealth University

BALANCE PERFORMANCE MEASURMENT IN A PHASE SHIFTED FEEDBACK ENVIRONMENT

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering at Virginia Commonwealth University.

By

Craig Alan Hoovler

B.S. in Applied Sciences, Concentration in Biomedical Engineering
B.A. in Mathematics
University of North Carolina, Chapel Hill, 2004

Director: Peter E. Pidcoe, P.T., D.P.T., Ph.D.
Associate Professor, Department of Physical Therapy

Virginia Commonwealth University

Richmond, Virginia

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Commercial technologies for the objective assessment of balance exist in clinical settings. Training requires integration of sensory information to produce a coordinated motor response related to balance. These systems have had measurable phase delays of up to 250ms in the visual feedback provided to the patient. This provokes an unnatural response, requiring prediction from the subject. The proposed research investigates the impact of visual feedback phase delays on the performance of weight shift tracking tasks in a population of individuals with no known balance deficits.

Visual feedback delays were investigated by simulating popular balance training software which utilizes force plates to measure center of pressure and display the results in a stimulus and response study. Ten healthy young-adult subjects with no known balance deficits were recruited to participate in this study. Subjects were asked to stand on a pair of force platforms that were linked to a computer. The system was designed to provide visual feedback corresponding to lateral weight shifts. A computer generated

target provided a moving stimulus the subjects attempted to match. The stimulus files presented approximately 20 seconds of movement in a periodic (sinusoidal) or non-periodic pattern. Stimulus frequencies ranged between 0.2 and 1.0 Hz with amplitude sufficient to require the subject to move safely within 50% of his/her base of support. Stimulus presentation was randomized and included both normal (control) and phase delayed (experimental) trials.

Results of the experiment point to a noticeable improvement of performance with repeated trials. Regardless of introduced phase delays, study participants improved their performances as they were exposed to more trials, suggesting learning and predictive behavior. Random stimuli produced no noticeable improvements in performance across days of testing, as expected. Visual biofeedback systems may skew performance assessments of balance training because they contain periodic stimuli that are predictable.

BACKGROUND

Introduction

Balance can be described as the ability of the body to maintain itself upright in relation to the ground and in response to movement. Balance is a sense of body position in space that is conveyed to the brain by a complex set of signals from the other sense organs of the body. Vision, the vestibular system, hearing, proprioception, and the somatosensory system all contribute to the brain's balancing system. There are nerves in the joints, skin, and muscles that all make the brain aware of the body's position and motion. The purpose of this research was to examine how a delay introduced into a visual biofeedback system would influence the performance of a stimulus-response driven balance task. In order to help understand this work, a review of vestibular physiology follows.

The Physiology of Balance

Vestibular Organs

The vestibular, or balance, system is fluid based, and is located in the vestibular apparatus. The vestibular apparatus is a membranous labyrinth located in the inner ear behind the temporal bone. The receptors themselves are two fluid filled compartments lined with hairs sensitive to motion. The inner compartment is filled with endolymph, while the outer compartment is filled with perilymph. The vestibular apparatus can be divided into the vestibule, which monitors static equilibrium, and the semicircular canals, which monitor dynamic equilibrium. Balance receptors send signals to the brain that can initiate reflexes to make changes needed in body and joint position during and after body movements. The vestibular system can be seen below in Figure 1.1.

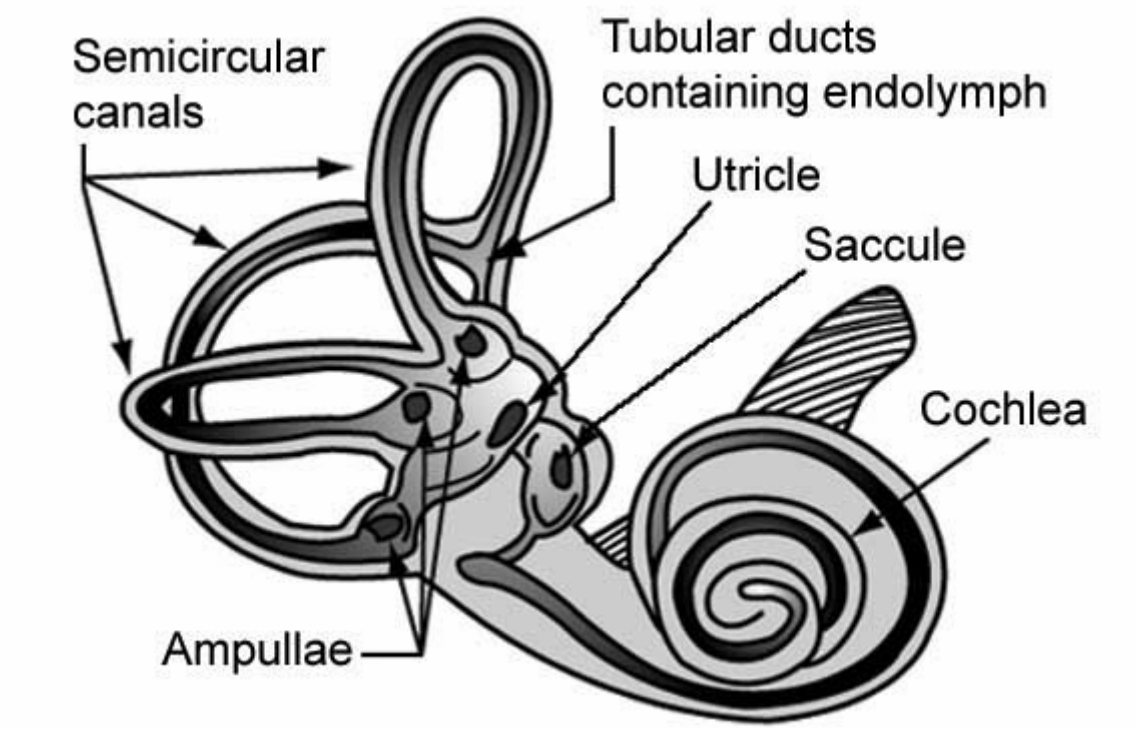

Figure 1.1 The Vestibular System – semicircular canals and otolith organs [1]

The vestibule is composed of the macular structures, known as the saccule and the utricle. The vestibule responds to linear acceleration and gravity. The maculae, or statolith organs, contain an otolith mass made of mucopolysaccharides and deposits of calcite crystals, or calcium carbonate. The mass slides across sensory hair cells as the body is subjected to translational (linear) accelerations. Forces of inertia cause the stereocilia (sensory hair cells) to bend. If the motion causes the stereocilia to bend towards the kinocilia (another sensory hair cell type), the nerve cells depolarize, causing excitation of the hair cells. If the motion causes the stereocilia to bend away from the kinocilia, the negative displacement causes hyperpolarization of the sensory hair cells, and inhibition. For the utricle, tilting the head forward or laterally, as can be seen in Figs 1.2 and 1.3, causes ipsilateral (same side) excitation, while tilting the head backward or medially causes a decrease (inhibition) of activity. For the saccule, activity increases for pitch movements forward and backward, as well as lateral and medial (roll) movements. The saccule also makes the person aware of vertical displacement of the head both upward and downward. Every orientation of the skull can be encoded by the brain due to the bilateral design of the vestibular system. The pattern of nerve activity from the statolith organs provides information about the position of the head in space.

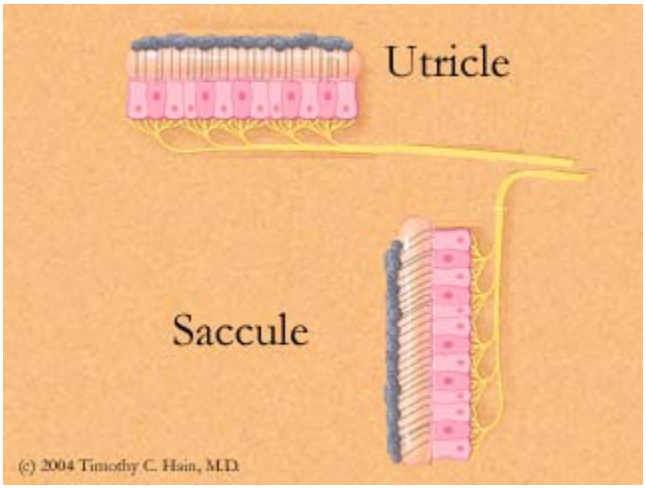

Figure 1.2 Otolith organs [18]

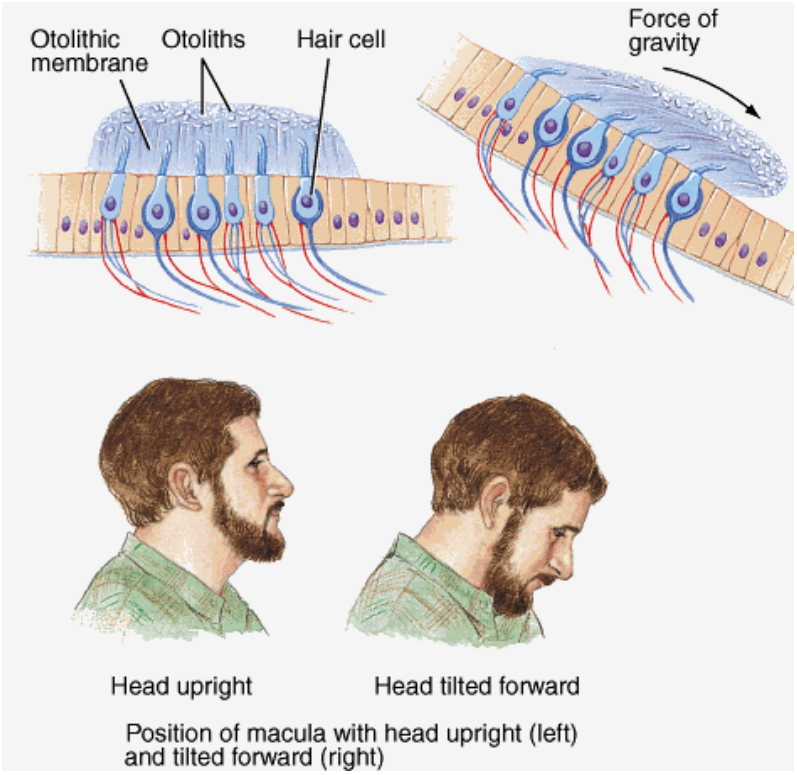

Figure 1.3 Gravity effects on Otolith organs [19]

The semicircular canals are known as the statokinetic organs and respond to angular accelerations. Like the statolith organs, the semicircular canals have developed bilaterally, with three canals on each side of the head. The canals themselves are closed tubes filled with fluid. At one end, there is an enlargement called the ampulla, which contains the sensory receptor cells. The cupula, a gelatinous membrane, lies above the receptor hair cells. The cupula's specific gravity is similar to the surrounding endolymph, and so only moves in response to angular accelerations, unlike the otoliths which are stimulated by translational movement. It spans the width of the canal and is dragged through the endolymph when the skull rotates. There is a period of time where the endolymph within the canals moves more slowly than the labyrinth itself, and therefore causes the cupula to stretch the walls of the canal in the direction opposite that of rotation. The process is illustrated in Figure 1.4. The stretching causes cilia to bend either towards or away from the utricle, which causes a change in nerve discharge rate. Bending of cilia towards the midline (utricle) causes increased discharge, while bending cilia away from the midline decreases the discharge rate. Therefore, increases in activity from the right horizontal semicircular canal correspond with decreases in activity from the left horizontal canal. Normally, as rotation continues, the cupula returns to a resting state as the endolymph catches up with the bony labyrinth during constant velocity rotation. Sudden stops and decelerations cause the endolymph to keep flowing while the bony labyrinth does not. In this case, the endolymph continues to be displaced in the direction of rotation temporarily. This type of response is considered viscoelastic. These canals are arranged perpendicularly to each other, and as such, can represent all possible

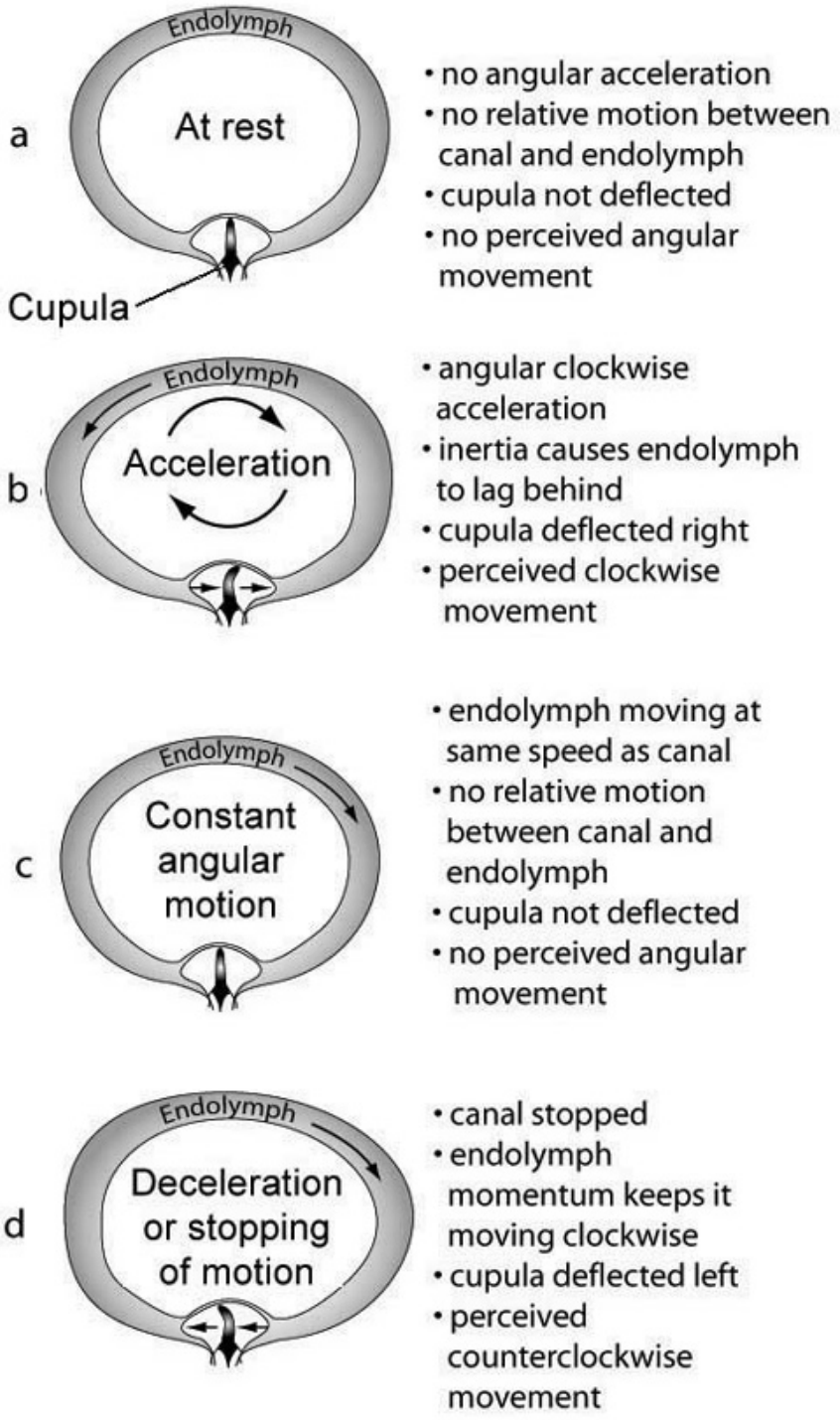

Figure 1.4 The effects of angular acceleration on the semicircular canals [1]

rotations around three primary axes. The three canals are the horizontal canal, the anterior vertical canal, and the posterior vertical canal. Therefore, the semicircular canals detect and measure angular accelerations in three dimensional space.

Neurology

In regards to the nerves that allow us to maintain our balance, the main afferents of the vestibular system end in the medulla. Inside the medulla, there is a region containing vestibular nuclei. The Bechterew's nucleus is considered superior and the Schwalbe's nucleus is considered medial. These nuclei receive their input from the semicircular canals. This input is then projected out through the medial longitudinal fasciculus nerve to innervate the extraocular muscles. The Deiter's nucleus is considered lateral, and receives information from the utricle. Here, the input is projected through the lateral vestibulospinal tract to the spinal cord motor neurons. These projections work heavily to maintain posture and reflexes. The inferior nucleus is called the Roller's nucleus. This nucleus receives information from the utricle, saccule, and semicircular canals and then sends this information to the brainstem and cerebellum through the medial longitudinal fasciculus. These nuclei also receive input from muscle and joint receptors in the neck, and serve to keep the head upright in space. A general understanding of the pathways involved in processing balance can be seen in Fig 1.5.

Figure 1.5 Balance Control Pathways
Reproduced with permission from Neurocom [15]

Reflexes

The vestibular system functions to maintain balance and coordination through the use of reflex actions that can be classified as either static or statokinetic reflexes. The static reflexes are mainly the result of input from the macula organs. Static reflexes include control mechanisms for upright posture and position of the limbs in three dimensional space. Compensatory eye rolling, where the eyes roll in the opposite direction of a head tilt to keep the pupils able to maintain a constant image orientation on the retinas, is an example of a static reflex. In the case of the head being tilted into a horizontal position, the eyes would roll opposite to keep the pupils in a vertical position. Movement reflexes, however, are brought about by movement, and include input from the macula as well as the semicircular canals. The lifting response is a statokinetic reflex, where extensor tonus is increased during free fall, but decreased during lifting. Cats being able to orient themselves upright and land on their feet during a free fall are examples of statokinetic responses. Pathways involved in these reflexes can be seen in Fig 1.5.

A specific type of statokinetic reflex that we see everyday is called nystagmus. Vestibular nystagmus is responsible for maintaining a particular direction of gaze. The reflex causes the eyes to move initially against the direction of head rotation, and is called the slow component. As the eyes reach the limit of lateral movement, the rapid component causes a quick jump in the direction of rotation to fixate on a new point in space. The clinical direction of nystagmus is the direction of the rapid component, and so, of the direction of rotation. The passive form of vestibular nystagmus is known as optokinetic nystagmus, which is basically a passive movement of the visual field.

CLINICAL

Vestibular Function Tests

There are several tests for vestibular function; two of the most common are the Barany Test and the Caloric Test. To test for vestibular functionality using the Barany test, a subject is seated on a Barany (rotating) chair and turned at a constant velocity for at least 10 revolutions. To test the horizontal canal, the head is tilted around 30 degrees forward, and will produce side to side eye movements, or horizontal nystagmus. To test the vertical canals, the head is tilted towards either shoulder at 90 degrees. Eye movement in this situation will be up and down. In the event that rotation is abruptly stopped during the test, a condition known as post-rotatory nystagmus will result, which is nystagmus in the opposite direction of rotation. In this test of vestibular function, it is important to prevent visual fixation. The way to avoid fixation and prevent measuring optokinetic nystagmus is the use of special glasses that make the subject myopic, or unable to fixate. If post-rotatory nystagmus is observed and the subject tries to stand up, he will turn or fall in the direction of the rotation. The post-rotatory nystagmus makes the person think he is spinning in the opposite direction, and so causes contraction of the contralateral extensor muscles.

Another test for vestibular function is the Caloric test. This test involves exposing the ear to warm or cold water, which in turn causes heat transfer, which can cause endolymph to rise or fall. The subject in this test tilts his head back 60 degrees, which places the horizontal canals almost vertically. This test also allows testing of the right or left horizontal canals separately. Since the outer edge of the horizontal canal is close to the superficial ear, or external auditory meatus, the water temperature can cause flow of endolymph and deflection of the cupula. This deflection is also known as caloric

nystagmus. Warmer temperatures cause nystagmus towards the exposed side, while cooler temperatures cause nystagmus away from the exposed side. The effects of this test normally last around two minutes, but shorter periods of nystagmus could indicate a disorder of the vestibular system.

More advanced testing can give quantitative measures of vestibular function. Electronystagmography uses electrooculography (EOG) to measure changes in electrical charges produced by the retinal-corneal potential using skin electrodes, or infrared oculography (IRO) that allows direct measurement of eye movements and eliminates artifacts present with EOG [16]. Central vestibular function is measured using nystagmus, reflex, and motion tasks. Eighth cranial nerve and labyrinth functions are evaluated according to response to a variety of stimuli. These tests allow for observation and quantification of nystagmus, and therefore, vestibular function.

Computer dynamic posturography (CDP) tests vestibular, visual, proprioceptive, and somatosensory senses. Subjects stand on a force-plate system that can measure body sway during different exercises and visual and postural conditions. Sensory organization tests (SOT) measure stability using stability conditions involving either a flat or a perturbed surface. The conditions applied are eyes opened, eyes closed, and perturbed vision. SOT compares normal sway with sway under the experimental conditions [16].

Limit of Stability testing (LOS) examines how well an individual can move their center of mass while maintaining their upright posture. LOS testing is useful for examining risks associated with falls and to help determine specific exercises to improve movement skills. These exercises should minimize the chance of falling during weight

shifts. A combination of these tests is ultimately used to determine individual patient needs. These needs will determine specific strategies for rehabilitation.

Clinical Problems

Two of the most common disorders of the vestibular system are kinetosis, or motion sickness, and vertigo. Kinetosis occurs when a strong stimulation of the vestibular system causes unpleasant sensations, including dizziness, sweating, nausea, and vomiting. Kinetosis can also occur when a person is not used to a specific type of vestibular sensation. Examples include rocking motions on a boat or if there is a discrepancy between sensory inputs, like reading during a bumpy car ride. Vertigo is the feeling of rotation or dizziness in the absence of movement. This feeling can result if there has been vestibular damage, most likely following trauma, infection, vascular occlusion, or exposure to toxic chemicals.

In the case of more serious disease or infection, the balance system can be severely damaged. Some of the most common are stroke, Multiple Sclerosis (MS), and Parkinson's disease. General complications with the ability to balance can arise as a result of natural aging as well. Diminished vision or touch senses, damaged nerves, or muscular damage can all affect the body's ability to balance. Research into physical therapy techniques may allow some patients to regain at least partial balance control. Most therapies involve retraining the muscle groups and reinforcing their communication with the brain.

Typical Therapy

Researchers have found that when parts of the balance system are damaged or destroyed, such as in an accident or through disease such as the numb feet experienced by diabetic patients, people may lose their innate ability to balance. Research suggests that after a period of rehabilitation, some subjects are able to regain their balance despite the loss of some sensory information [2]. Therefore, if rehabilitation can successfully retrain balance activities, the question becomes, which rehabilitation strategy is most effective?

Vestibular Rehabilitation Therapy (VRT) can be a useful tool. This strategy consists of simple exercises designed to restore the brain's normal use of the visual, vestibular, and somatosensory (body nerves) inputs. VRT can be a useful strategy for simple dizziness and vertigo, as well as in speeding central compensation after a permanently damaged set of vestibular sensors [3, 4, 16]. Several weeks or longer of consistent rehabilitation exercises can be required to notice a substantial improvement. In the event of missed exercises, symptoms can return [4, 16].

Various research groups studying balance recovery, often with stroke patients, highlight two other rehabilitation strategies based on CDP and LOS testing. Some studies present their experimental groups with three treatment styles [17]. Static balance training utilizes weight shifting with visual biofeedback, while dynamic balance training uses games designed to enhance center of mass movements. The third group functions as a control group, using only traditional rehabilitation. A majority of studies looking at visual biofeedback were examining whether patients who were given visual representation of their movements would be able to improve their balancing ability significantly better than their control group (or other experimental group) counterparts.

Although studies suggest that visual biofeedback is effective for increasing stance symmetry [20], functional balance ability improvements are still being investigated. While some claim conclusive evidence in favor of visual biofeedback [21, 22], others claim to refute its effectiveness as being no more beneficial than regular therapy [20].

Purpose

Stimulus-response tracking tasks have become part of balance retraining in many rehabilitation settings. In these systems, balance performance is quantified by measuring changes in a subject's center-of-pressure (COP) or center-of-mass (COM) as they weight shift in response to a supplied visual stimulus. This response is typically displayed to the subject so that they can more precisely track the displayed stimulus. From the collected data, errors between the stimulus and response are computed and used as one performance measurement. All information is displayed visually in real time. Since a finite period of time is required to compute and display response data, delays may exist in the reporting of that data to the subject. These feedback delays may influence performance measurement.

Previous studies investigating the effectiveness of the visual biofeedback systems neglected to account for this delay effect associated with feedback systems. The research presented here was designed to test whether or not subjects presented with visual biofeedback while using a force-plate center of pressure system were affected by an imposed feedback delay. To test this, delays were introduced between the movement of the subjects and the visual feedback they received on the monitor in front of them. The introduction of a phase delay allowed us to quantify study participants' abilities to track a stimulus-response task. If participants were able to track, were the subjects able to adjust

for the introduced delays? If so, how much could they adjust for, and how much was too much to compensate for?

Research Question:

How does feedback delay influence the performance of a stimulus-response driven balance task?

Hypotheses:

1. Phase delayed visual feedback will result in decreased tracking gains and these gains will further decline with increased stimulus frequencies.
2. Predictive phase compensation will occur during periodic tracking tasks regardless on the imposed response phase delay.
3. Predictive phase compensation will not occur during non-periodic tracking tasks.

Specific Aims:

1. To test the impact of visual feedback delay on response gains. This will be performed using stimuli at periodic (predictable) frequencies ranging from 0.2 Hz to 1.0 Hz and on non-periodic (non-predictable) stimuli that contain discrete non-harmonically related frequencies.
2. To test the limits of the prediction using controlled phase-delayed responses. These will be described as a function of stimulus frequency and imposed phase delay.
3. To determine the influence of response phase delay on non-predictable stimuli.

METHODS

General

As mentioned in the background, the focus of this project was to test the effect of phase delays on feedback-based balance training. In feedback-based balance training, subjects are commonly asked to stand on force plates that are linked to a computer-based data acquisition system. The force plates provide information about left-right and anterior-posterior weight shifts. The computer interprets the data and presents a visual representation whose movement is linked to these weight shifts. This is the response. A computer generated target provides a testing and training environment that is often used in balance training in impaired clinical populations. This is the stimulus. In this environment, subjects are asked to match their responses to the stimulus. Fig. 2.1 illustrates a common force plate-based balance system.

Figure 2.1 Common balance feedback systems
Reproduced with permission from Neurocom [15]

To evaluate current feedback-based balance systems, it was necessary to create a program similar to one of the popular visual biofeedback systems that are available commercially. Like the mainstream systems, the data acquisition system read subject position in space from two force plates on which the subject stands. Each force plate contained four strain gages, each placed in the corners of the individual force plates. Each strain gage relayed the proportional amount of the person's weight being placed in the four quadrants of each force plate represented by strain gages and their location. This proportional weight distribution was indicative of the location of their center of pressure at a given instant. Therefore, each center of pressure position in space was able to create a unique combination of readings from the eight total strain gages (four per force plate). This information was then used by the computer to create a visual representation on-screen. In the experiments for this project, the computer generated stimulus was a simple box, and the visual representation of these weight shifts was a crosshair that moved horizontally with movements by the subjects. Fig 2.2 is indicative of what a participant would see on the monitor in front of them. In this study, there would also be a target box on the monitor in addition to the cross-hair.

The position of the box is determined by imported files that the program reads. These files are basic sinusoidal waves, with frequencies of 0.2 Hz, 0.4 Hz, 0.6 Hz, 0.8 Hz, 1.0 Hz, and a file consisting of a combination of 3 disharmonic sine waves, to create the appearance of random movement by the target. The subject is instructed to try to move with the box. As they shift their weight, the cross-hair will move with them. If the

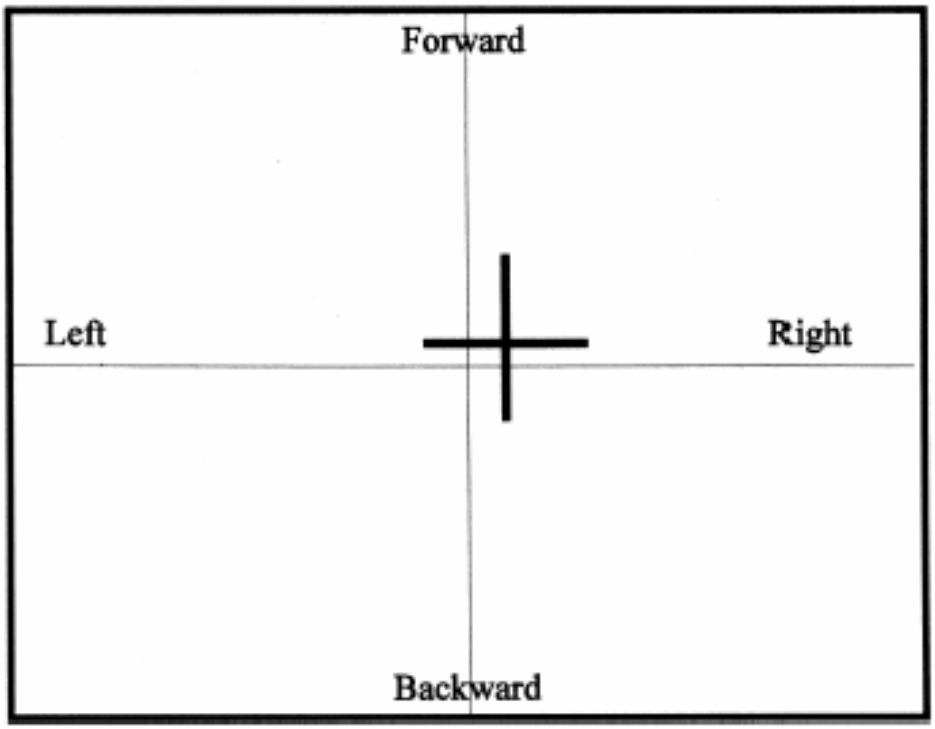

Figure 2.2 Typical feedback on a monitor [22]

cross-hair overlaps with the box, there is a color change in the target, signifying that they are matching the movement of the target, as instructed.

Hardware

The force plates are essentially hollow wooden boxes. Each consists of a base padded with a light foam, three sides of wood, a fourth side of removable plastic (for easy access to the interior), and a metal plate on top of which the subject stands. Inside the box are four sturdy metal rings, each positioned in a corner at a forty five degree angle to the sides. The base is 15.75 inches squared. The sides of the box are 15.75 inches wide by 0.75 inches thick, with a height of 4.75 inches. The metal rings sit at the same height as the sides. The metal plate on top of the system is 14 inches squared, and sits on top of the metal rings. The metal plates protrude up by 0.25 inches, or a total height of 5 inches. Each ring has four strain gages, attached to the inner and outer surfaces of the ring. This configuration is called a load cell. As the ring deforms due to the weight shifts of the subject, the strain gages change resistance, which produces a small voltage change in the bridge circuit. This voltage is read by the DAQ and interpreted by the computer to represent a force. The voltages are converted to force using calibration equations. The load cells were independently calibrated. The four voltages sent by the four gages are combined by the computer to signify a position in space (center of pressure). Then, the centers of pressure from both force plates are combined by the program, which assumes the two force plates are sitting next to each other in space. Center of pressure calculations are results of the physical geometry of the system. The coordinates are displayed on the monitor and scaled to the display. The display is maximized using an individual subject's region of stability. The whole system was placed 27 inches from the

computer, with the monitor elevated on a cart to 29.5 inches, with a 17 inch CRT monitor.

Software

The program is capable of exposing the subject to five different types of feedback. These include anterior/posterior tracking, medial/lateral tracking, two dimensional tracking, random box placement, and stack bars. Generally, these diagnostic tests allow physical therapists to quantify a patient's ability to control the movement of their center of gravity. The anterior/posterior tracking and medial/lateral tracking look for the patient's ability to rhythmically shift his/her weight in one plane. The box placement requires more control in the form of movement to a box randomly placed in two-dimensional space, as opposed to simply shifting in one dimension. The range where a patient has the ability to create controlled movements helps to define the "region of stability" for the individual patient, which is then used when drawing the display. For the purposes of this project, we are only concerned with the first function, medial/lateral feedback. The supplied files consist of various sinusoids and combinations of sinusoids. The sinusoids provide periodic, predictable movement, while the combinations of sinusoids create non-periodic, non-predictable, movement. These files cause the target box to move horizontally back and forth across the screen. Each trial's movement is determined by the imported sinusoid files.

Phase Delay

To place a phased delay into the program, we used an array based on the queue concept that reflected a delay of a given number of clock cycles. Using a header file allowed us to initialize a timer to capture the value of the computer's clock relative to the start of the program. Using an external file call, the values of the timer for every cycle during each run were written out to "timer.bin," for a total of 2000 timer values for each run, or a total of 18000 total points for a given trial. By examining the values on "timer.bin" we were able to see the elapsed time for each clock cycle. What we found was every 6^{th} and then every 7^{th} data point was a factor of ten larger than the others. This was attributed to the need to dump the storage buffers that the program uses for storing and displaying its data from the force plates. Although each cycle was not exactly the same, the non-dump time values averaged .00016 seconds, with a standard deviation of less than .01, which was small enough to be considered the same for every cycle of the computer. Once this was determined, the introduction of a phase delay between the actions of the subject and the representation of their actions that were drawn on the monitor was able to be programmed using a queue.

Due to the extremely small clock time and the similarities between subsequent cycles, the easiest method to introduce a delay was through the use of a linear array. The simplest version of a linear array in the C programming language was a queue. In the particular style of coding chosen, the queue used dynamic memory allocation, which was very useful for keeping the system robust. The queue functioned by creating an artificial storage site within the computer's memory. As data was recorded, it was placed in the first spot in the array using a command called "Push." The amount of delay needed

determined the number of data points that were “pushed” into the stack before any were called up and used to display the subject icon. The command for using the first item in the queue was called “Front.” Immediately after reading the “front” value, another command, “Pop,” was called to remove the data point from the queue, so that it was not read a second time. This process of loading, reading, and removing data values from the queue was the basis of the delay programming.

The program was also able to run without phase delays. The runs with no introduced delays served as the control group. Along with a mode that used a zero delay setting, the program was given a “phase” mode. When accessing the file from DOS, if the file name was called with the argument “phase” after it, a flag inside the program was set to true, which turned on the functionality of the phase testing. Once in phase mode, the program read a delay amount from the parameter file for each of the nine trials presented to a subject on each of four days of testing. This robustness allowed all nine trials to have the same delay time or to vary the amount of phase shifting throughout the course of a test day.

Data Collection

Subjects were asked to come in on four consecutive days to allow us to gather data. When the subjects came into the lab, subjects were asked to stand on the force plates and direct their attention to the monitor in front of them. They were told that the box on the monitor represented a target and the cross represented their body’s position in space. They were told that as the target box moved, they should try to move their body to match the position of the target box in space. They were also told that if they were correctly matched their movements with the target box, there would be a color change on the

screen. Then, they were simply allowed to react to the program. They were not allowed practice time. Their first day of testing was their first interaction with the program.

Each participant reacted to nine trials on each of four days of participation. On the first day of trials, Day 01, all participants were presented with a random order of sinusoids, all with zero delay, to establish base-line performance. The possible stimuli consisted of waves of 0.2 Hz, 0.4 Hz, 0.6 Hz, 0.8 Hz, 1.0 Hz, and a randomized frequency consisting of the sum of 0.3 Hz, 0.8 Hz, and 1.6 Hz waves. On the three other days, Day 02, Day 03, and Day 04, the participants were presented with a random assortment of sinusoids, but with randomly assigned phase delays of either 0.25, 0.50, or 0.75 seconds.

To analyze the data, the program recorded the position of both the stimulus and response icons. This real time recording of the data was not affected by the introduced delays. Therefore, we were able to record the position of the subject's body in space relative to the target even while the image of his position is being delayed on the screen.

Phase Responses

For a phase delayed response trial, if a study participant correctly tracked their stimulus target with their center of pressure movements, their crosshair representation (their visual biofeedback) would appear to lag behind on the screen, while the recorded phase values would appear close to zero. If they were instead able to track the target and compensate for the introduced delays, the icons would match (or be close to matching) and the phase values would be positive (leading). If the subject fell considerably behind, the phase values would be negative (lagging).

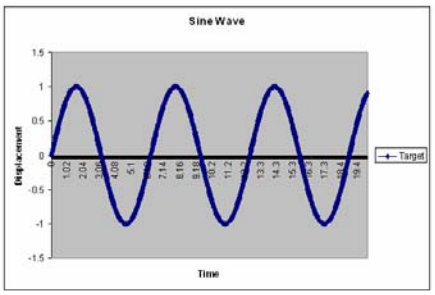

Figure 2.3 Exact Match

Figure 2.3 illustrates an exact match between subject movements and the movements of the target. Figure 2.4 shows the performance of a subject who was ahead of the target, indicating a phase lead. Figure 2.5 shows the performance of a subject who was behind the target box in his movement, indicating a phase lag. The larger the magnitude of the phase difference, the farther the subject's movements were from the stimulus box. Positive phase values indicate the participant was leading the box with his movements, demonstrating anticipatory movements. Negative phase values indicate the participant was lagging behind the box with his movements, suggesting a more reactionary response.

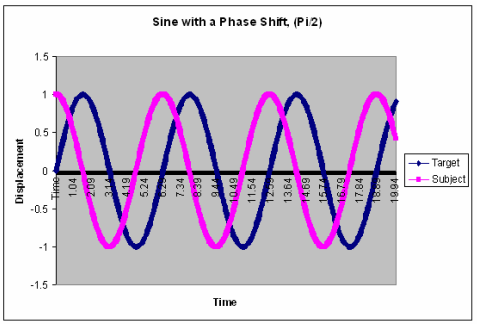

Figure 2.4 Phase Lead

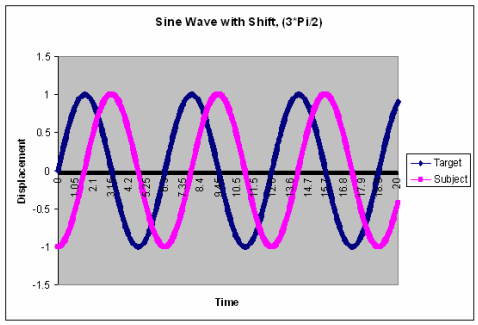

Figure 2.5 Phase Lag

Since period of the stimulus wave and the frequency are inversely related, as the stimulus frequency was increased, we decreased the amount of time a study participant had to react to the movements of the target box.

$$T = \frac{1}{f} \qquad\qquad f = \frac{1}{T}$$

i.e. If frequency is 0.2 Hz, period is $T = \frac{1}{0.2} = 5$ seconds

However, if frequency is 1.0 Hz, period is $T = \frac{1}{1.0} = 1$ second

freq(Hz)	0.2	0.4	0.6	0.8	1	Random
T(sec)	5	2.5	1.67	1.25	1	??

Table 2.1 Stimulus Frequency(f) and corresponding Period(T)

Table 2.1 lists the stimulus frequencies used for this study and their corresponding periods. In the case of the random stimulus, it was not possible to calculate a period.

Analysis

The data was organized by both phase delay and frequency. Two sets of Matlab m-files were created to examine the data to look for trends across the days based on frequency and delay. The m-files also took into account whether the data was presented starting with a left or right direction. This was intended to increase robustness in case of future experiments. However, for the purposes of this experiment, the directionality did not matter, so the gain and phase magnitudes of data from files from same day/frequency/delay were averaged together to create data to be analyzed later. Each subject's data was separately read in, as well as an average and standard deviation of all subjects for the trial run in question. The programs featured a sampling rate of 100 Hz. This sampling frequency created a frequency resolution of 0.1 Hz. The averaging and standard deviation calculations were performed in Excel. To ensure correct reading, the program graphed the data points in the time space.

For the purpose of this experiment, we were interested in gain and relative phase. After verifying that the correct data has been read in by displaying the time space graphs, the Matlab program performed fast-Fourier transforms using the "fft" command, power calculations by multiplying the transform by its conjugate, and used the command "max" to find the peak of the transform's power spectrum. Gains were found by comparing the ratio of the peak heights of the power spectrums of the sinusoidally driven signal relative to each subject's response. Since the random stimulus was actually a sum of 0.3 Hz, 0.8 Hz, and 1.6 Hz signals, to find gain response, we compared peaks at discrete points representing those frequencies in the power spectrum. For relative phase calculations, we smoothed out erratic response data using a moving boxcar window method, also known

as a linear envelope, and then compared zero crossings of the stimulus and response waveforms. The linear envelope method filtered the rough data by examining an odd number of data values, averaging them, and placing that averaged value as the midpoint value of the old filter in a new array of smoothed data values as the first point. For this experiment, the size of the filter was set to 151 data points. This process was repeated across the entire set of response data, shifting one point forward for each iteration. One negative consequence of the linear envelope method is the loss of some data at the beginning and end of the data stream where the envelope doesn't have enough points to average. The amount of data lost was equal to half the size of the filter. In this case, 75 points were lost at the beginning and end of the data. This loss was due to the need to use the first 151 points (the filter size) to average and create the 76^{th} data point. Similarly, to create the 76^{th} from last data point, the program needed the values of the last 151 data points.

The Matlab code concluded by graphing out the gain and relative phase values. Depending on which element was being examined determined which horizontal axis was used. Either the axis examined across all days or across the range of the delays we were examining.

RESULTS

To evaluate the effects of phase delays on balance training performance, it was necessary to look at subject response over a range of frequencies and with a variety of delay times. Once viewed in time space, it was also necessary to analyze the gain and phase responses of the subjects relative to the target they were chasing.

Subject Responses

Observing subject participation over the course of four days in time space showed greater error with larger phase delays. Figures 33- 3.6 illustrate the error. In the following graphs, the first waveform in the first column represents the stimulus, while the graphs below it in the first column are the averaged responses for all subjects. The second column represents the error, calculated as the difference between stimulus and response.

Horizontal axes are in centiseconds, while the vertical axis is in terms of displacement from center and is a percentage of the Region of Stability (ROS). Centiseconds were chosen over the traditional seconds or milliseconds because it allowed the analysis to have a correspondence of one hundred points being equivalent to one second of the experiment.

The random frequency stimulus in Figure 3.6 was used as a control. The random frequency stimulus was a sum of three sinusoids and served as unpredictable for study participants. The response waveforms in Figure 3.6 appeared to support the unpredictability of a sum of sines.

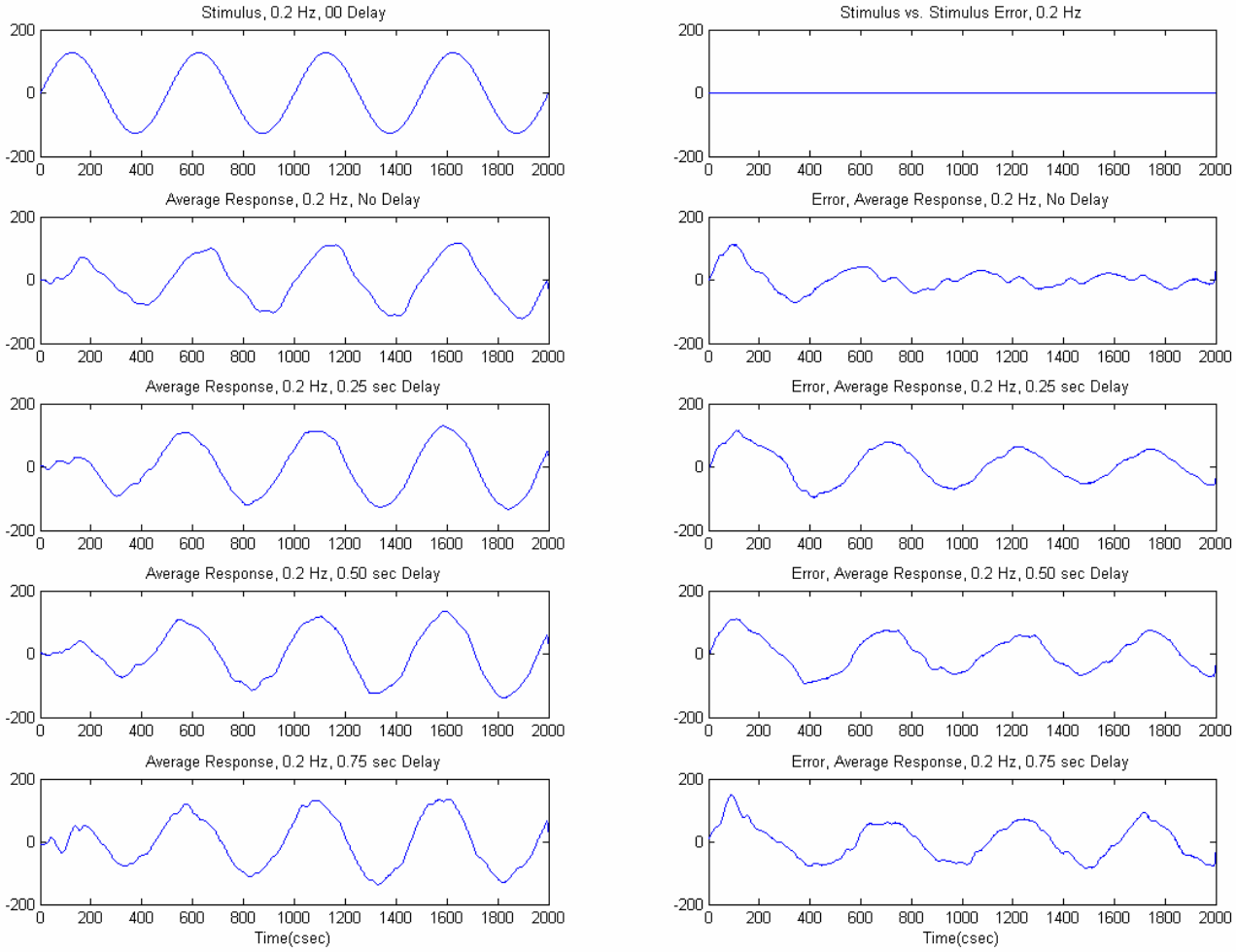

Figure 3.1 -- 0.2 Hz Responses

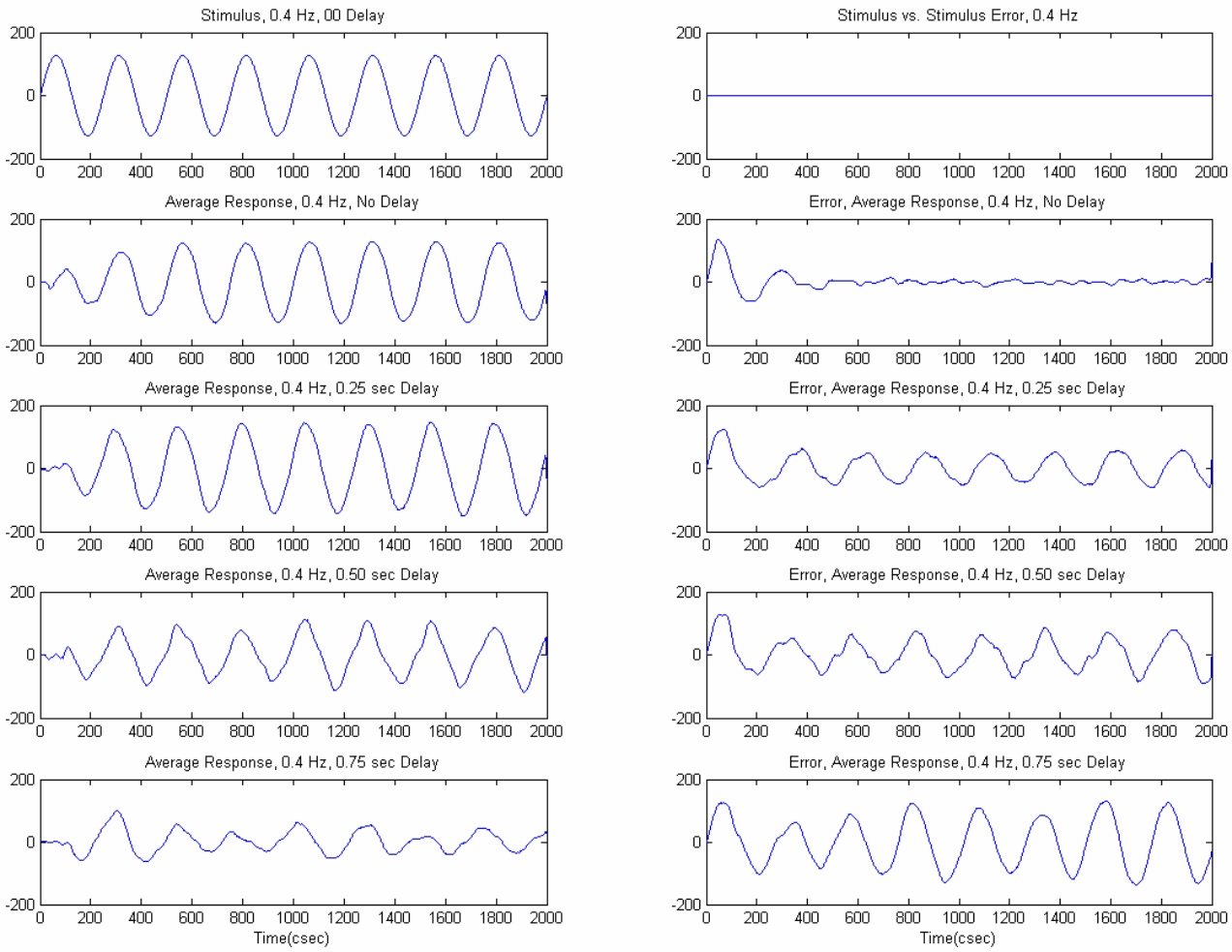

Figure 3.2 -- 0.4 Hz Responses

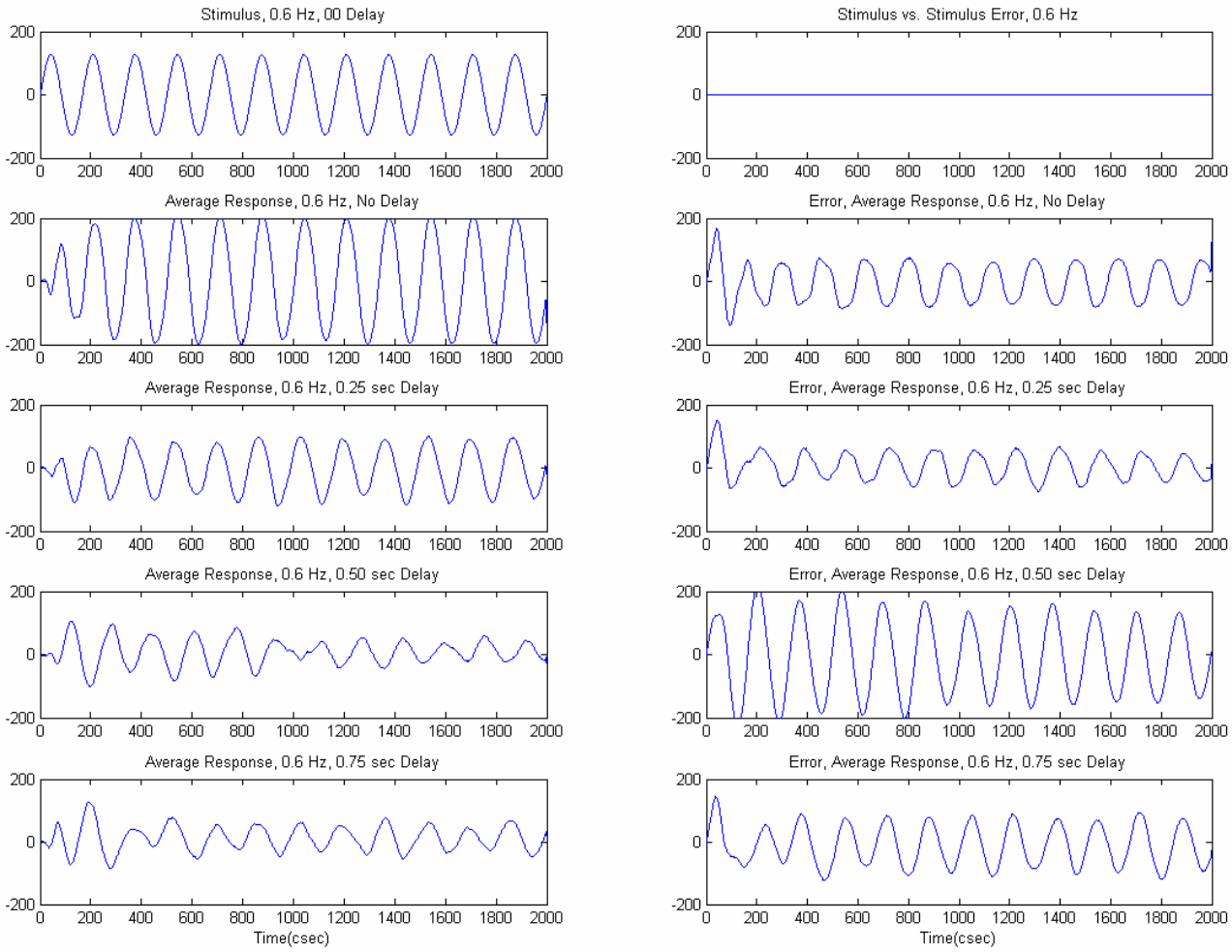

Figure 3.3 -- 0.6 Hz Responses

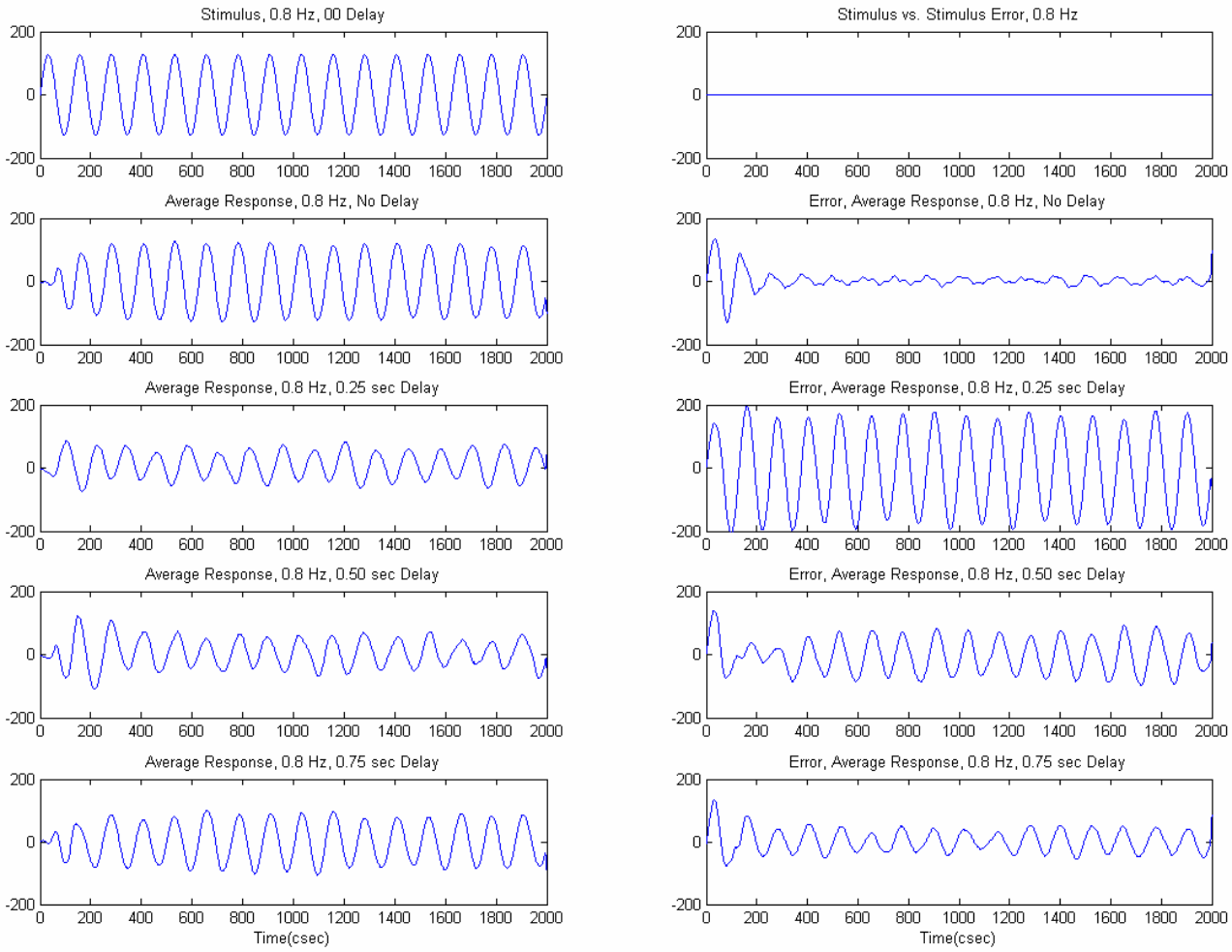

Figure 3.4 -- 0.8 Hz Responses

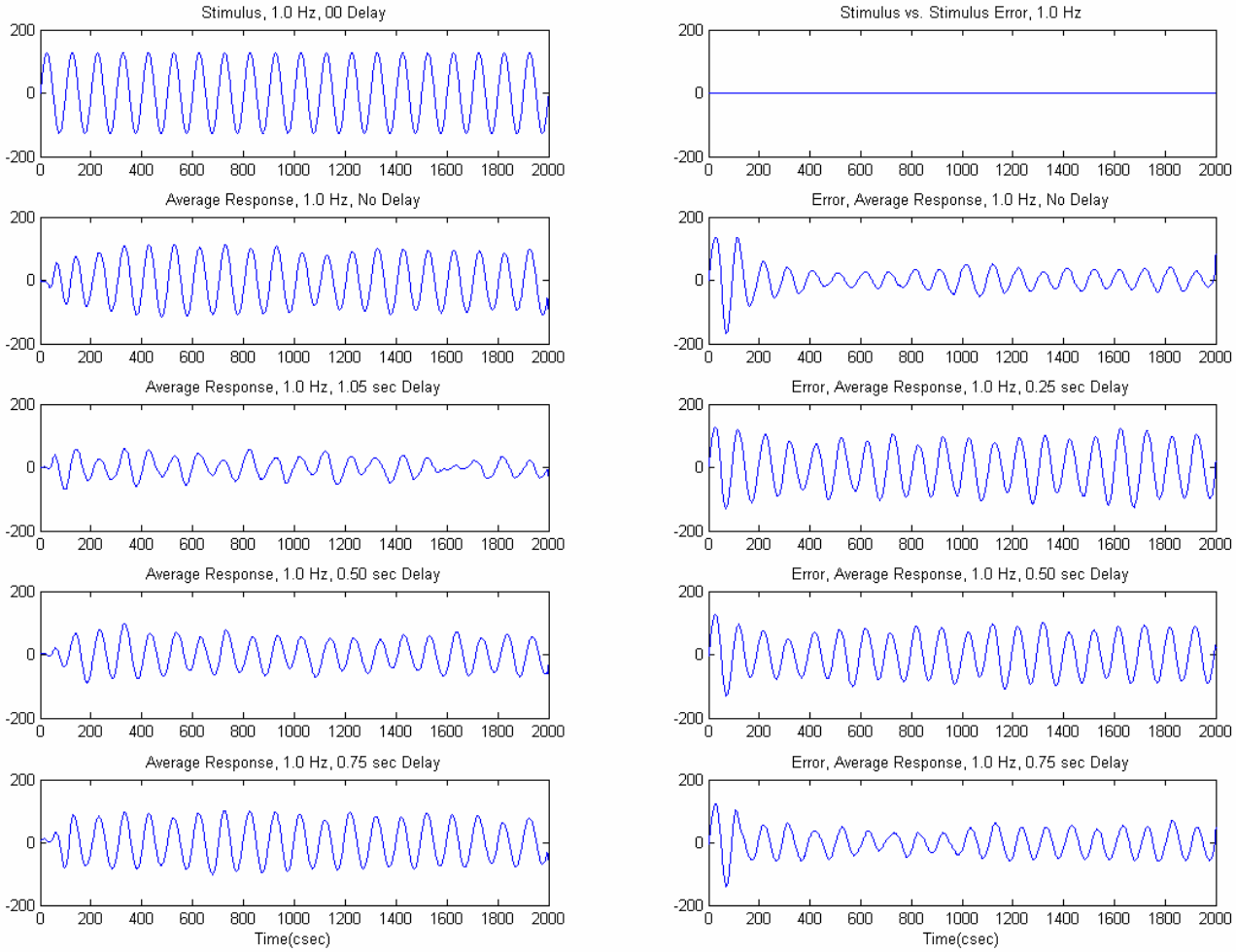

Figure 3.5 -- 1.0 Hz Responses

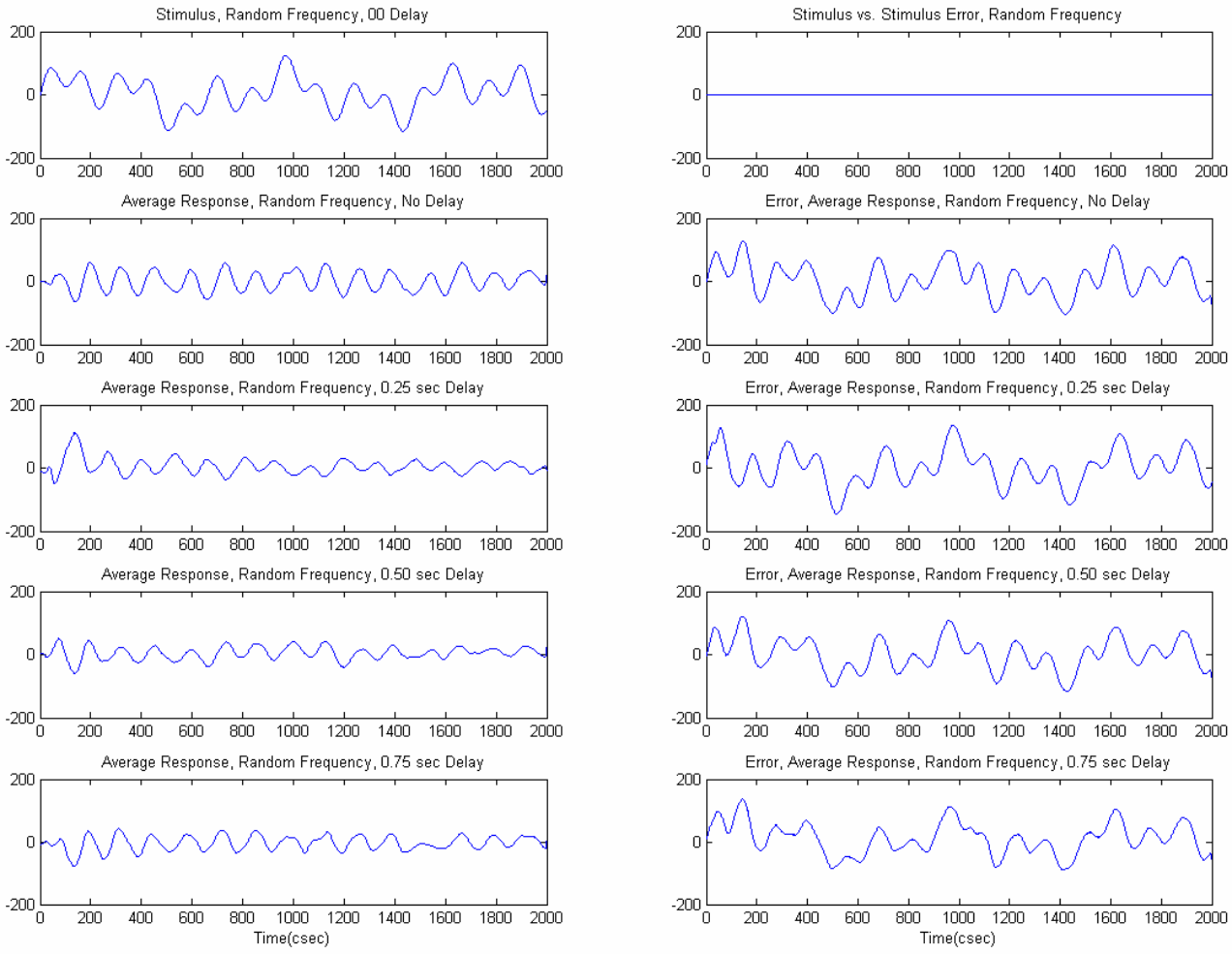

Figure 3.6 -- Random Frequency Responses

Gain Responses

To further evaluate temporal data on the performance of study participants, a frequency response was performed. It was necessary to compare the gain responses of individual participants. Along with calculating the individual gain responses, the gain data was averaged and emphasized with standard deviation lines. Gain responses were found as a ratio of the magnitude of the Fourier transform of the participant's response relative to the magnitude of the Fourier transform of the stimulus at the stimulus frequency. The gain values were computed through Matlab by comparing peaks of the discrete Fourier transforms (dft) of the time space data for the target and the subjects.

$Gain = \left(\frac{V_{Out}}{V_{In}} \right)$ when examining voltages, similarly here $Gain = \left(\frac{Peak_{dft(\mathrm{Re}\,sponse)}}{Peak_{dft(Stimulus)}} \right)$

For a target stimulus frequency of 0.2 Hz, the primary peaks on the discrete Fourier transforms of the movement were present at 0.2 Hz. For a target stimulus frequency of 0.4 Hz, the primary peaks on the discrete Fourier transforms of the movement were at 0.4 Hz. For a target stimulus frequency of 0.6 Hz, the primary peaks on the discrete Fourier transforms of the movement were present at 0.6 Hz. For a target stimulus frequency of 0.8 Hz, the primary peaks on the discrete Fourier transforms of the movement were present at 0.8 Hz. For a target stimulus frequency of 1.0 Hz, the primary peaks on the discrete Fourier transforms of the movement were present at 1.0 Hz. For the random target stimulus, the Fourier transform revealed multiple peaks, which was because the random signal was the sum of multiple sines. Those stimulus peaks appeared

at 0.3 Hz, 0.8 Hz, and 1.6 Hz, which were the sines added together. The response data revealed similar peaks. Since the primary peaks for movement for the target stimuli corresponded with the primary peaks for movement for the response data, gain calculations were simply a ratio of response peaks relative to stimulus peaks.

For test runs presented with no delay between subject response and visual feedback, gain reached a peak of around 1.0 with a frequency of 0.6 Hz. For frequencies above and below 0.6, there appears to be a slight drop in gain values. The emphasized lines above and below the average gain plot represent the averaged valued plus (above) and minus (below) the standard deviation of the averaged gain values.

For Day 01, 0.2 Hz stimulus, it should be noted that this was the first trial attempt for all participants, and therefore its values may be skewed due to learning the program at the beginning of testing. The first evaluation looked at values of gain where there was no delay.

Average Gain Response, no delay, by stimulus frequency

		Gain Values of Subjects			No Delay
	Averages based on Frequency of Stimulus				
	Frequency				
Subject	0.2	0.4	0.6	0.8	1
Avg	0.55	0.84	1.03	0.93	0.69
STD	0.11	0.16	0.21	0.30	0.32
A	0.59	1.08	1.22	1.20	0.76
B	0.37	0.73	0.91	0.76	0.39
C	0.57	0.74	1.07	1.07	0.72
D	0.59	0.93	0.64	0.16	0.11
E	0.70	1.06	1.20	1.10	1.00
F	0.63	0.66	1.11	1.19	1.20
G	0.61	0.84	1.05	1.00	0.45
H	0.48	0.97	1.32	1.11	1.06
I	0.64	0.94	0.94	1.01	0.68
J	0.53	0.64	0.71	0.73	0.43
K	0.37	0.66	1.13	0.91	0.75

Table 3.1 Gain Values for No Delay

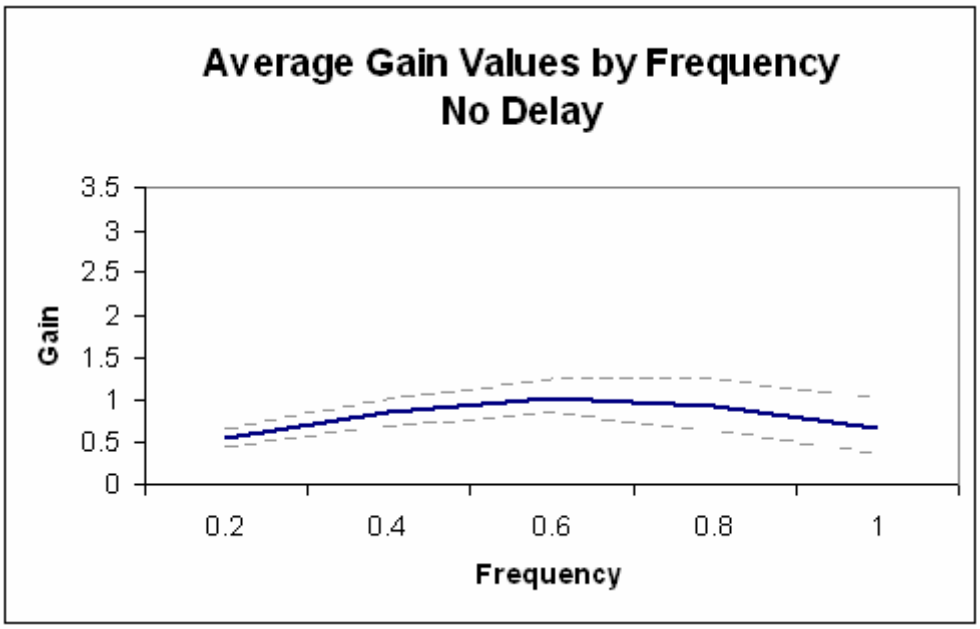

Figure 3.7 Gain Values for Frequencies presented with No Delay

With no delay introduced, the gain response for the various presented frequencies appeared to indicated tracking success for all frequencies, with the strongest performance for a stimulus frequency of 0.6 Hz.

Average Gain Response, 0.25 second delay, by stimulus frequency

	Gain Values of Subjects			*0.25 sec delay*	
	Averages based on Frequency of Stimulus				
	Frequency				
Subject	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Avg	0.74	1.13	0.79	0.30	0.27
STD	0.21	0.31	0.32	0.17	0.14
A	1.26	1.60	0.65	0.63	0.24
B	0.70	0.94	0.57	0.43	0.36
C	0.77	1.44	1.25	0.21	0.13
D	0.81	0.87	0.57	0.06	0.39
E	0.75	1.22	0.68	0.22	0.27
F	0.73	0.96	0.66	0.24	0.18
G	0.38	0.96	0.81	0.22	0.26
H	0.80	1.58	1.46	0.55	0.56
I	0.68	1.20	1.05	0.29	0.11
J	0.73	1.08	0.51	0.25	0.34
K	0.55	0.59	0.51	0.16	0.13

Table 3.2 Gain Values for 0.25 second Delay

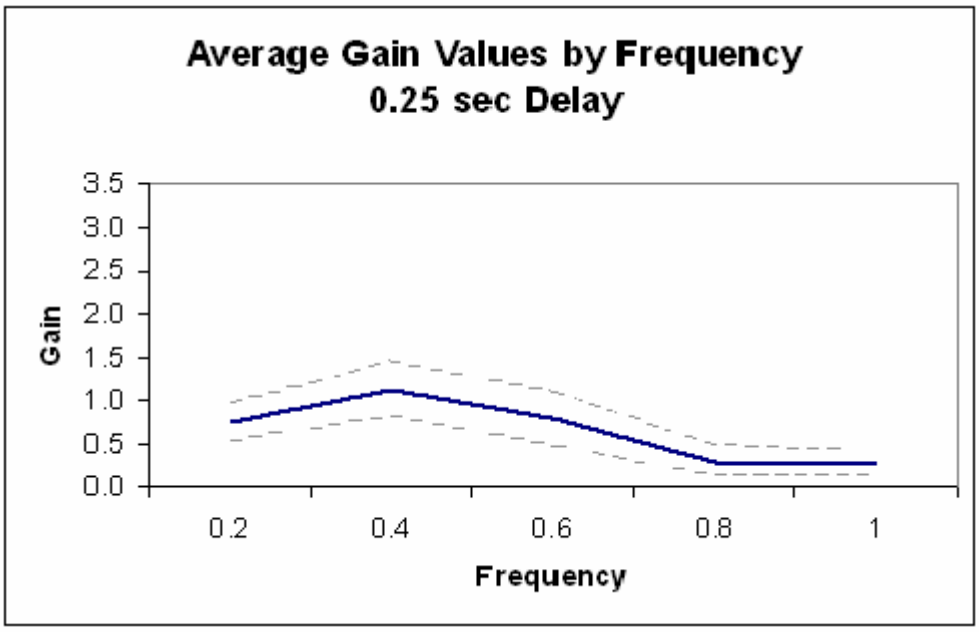

Figure 3.8 Gain Values for Frequencies presented with 0.25 second Delay

With the smallest of the delays presented, the gain values peaked at 0.4 Hz, with an average around 1.0, and dropped for the higher frequencies. This demonstrated difficulty tracking with a 0.25 sec delay for frequencies above 0.4 Hz.

Average Gain Response, 0.5 second delay, by stimulus frequency

	Gain Values of Subjects			*0.50 sec delay*	
	Averages based on Frequency of Stimulus				
	Frequency				
Subject	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Avg	0.83	0.67	0.31	0.25	0.46
Std	0.32	0.30	0.18	0.17	0.33
AC	1.21	0.54	0.56	0.67	1.32
AR	0.84	0.47	0.21	0.34	0.70
CB	1.39	0.73	0.18	0.13	0.56
DB	0.62	1.06	0.07	0.10	0.25
DL	0.69	0.62	0.20	0.20	0.26
EB	0.93	0.48	0.18	0.44	0.45
HO	0.45	0.32	0.19	0.25	0.42
JR	0.88	1.12	0.61	0.15	0.22
MM	1.02	1.14	0.24	0.14	0.15
PR	0.84	0.53	0.46	0.19	0.56
RR	0.28	0.37	0.49	0.15	0.21

Table 3.3 Gain Values for 0.50 second Delay

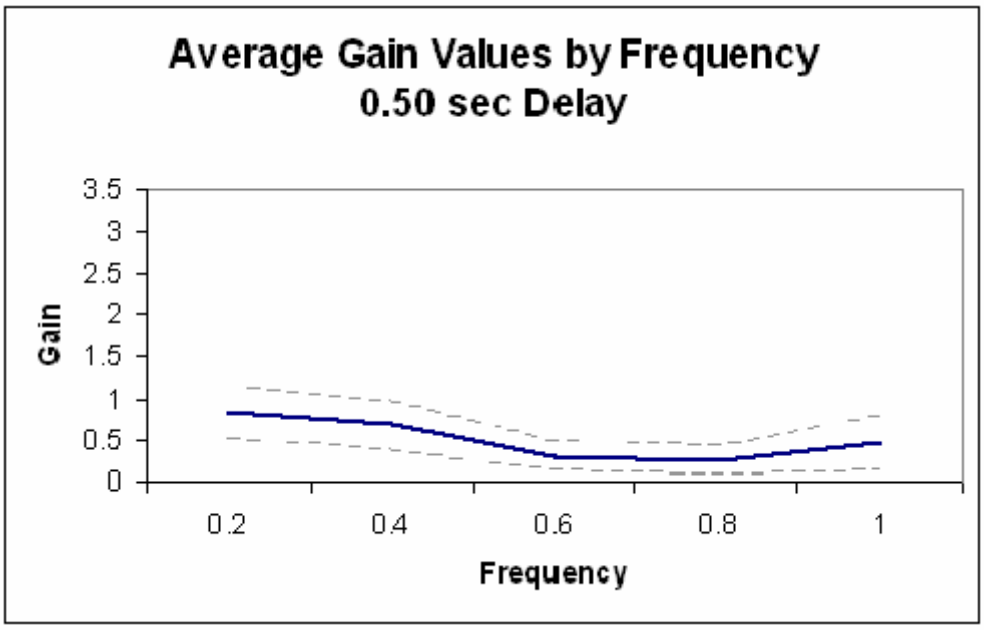

Figure 3.9 Gain Values for Frequencies presented with 0.50 second Delay

With the increased delay, the 0.2 Hz stimulus showed an average gain around 0.8, with higher frequency values showing tracking difficulty.

Average Gain Response, 0.75 second delay, by stimulus frequency

	Gain Values of Subjects			0.75 sec delay	
	Averages based on Frequency of Stimulus				
	Frequency				
Subject	0.2	0.4	0.6	0.8	1
Avg	1.01	0.32	0.22	0.55	0.49
STD	0.37	0.25	0.10	0.35	0.29
A	1.61	0.31	0.38	1.39	0.40
B	1.20	0.21	0.30	0.81	0.24
C	1.50	0.25	0.05	0.75	0.69
D	0.88	0.13	0.14	0.14	0.18
E	0.65	0.22	0.26	0.28	0.48
F	1.02	0.17	0.18	0.36	1.04
G	0.49	0.22	0.21	0.59	0.61
H	1.06	0.94	0.29	0.37	0.38
I	1.21	0.65	0.11	0.28	0.92
J	0.52	0.32	0.34	0.66	0.23
K	0.93	0.14	0.12	0.42	0.23

Table 3.4 Gain Values for 0.75 second Delay

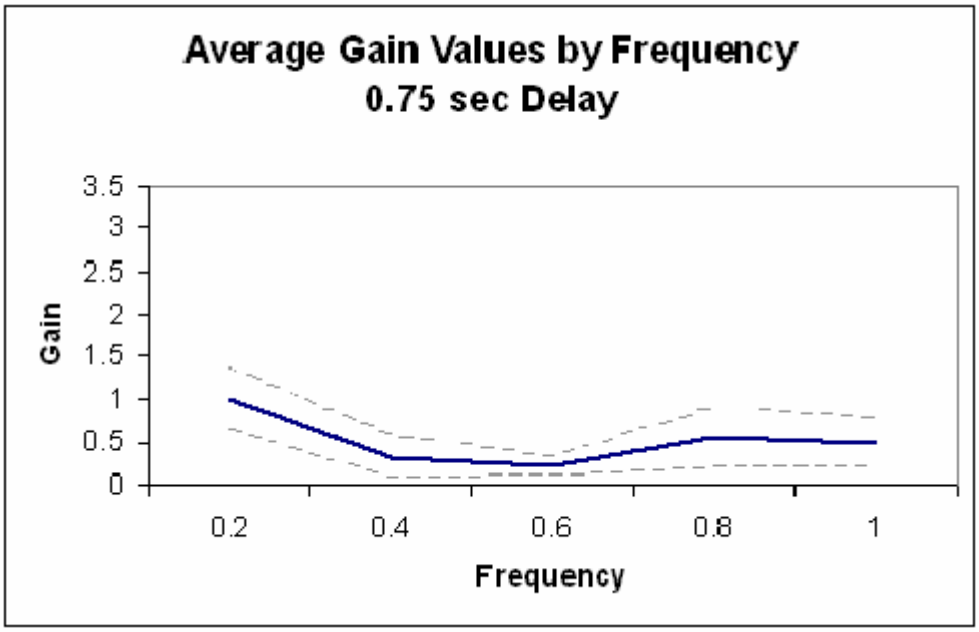

Figure 3.10 Gain Values for Frequencies presented with 0.75 second Delay

Again, with the delay increased to 0.75 seconds, gain values sat around 1.0 at 0.2 Hz, and drop quickly for the higher frequencies.

The above gain graphs attempted to show any gain trends by the delay presented. Although some useful information may be gleaned from those graphs, it was also important to break down the information and be able to compare the day of testing and the delay presented on the same graph. The following graphs show a distribution of gains broken down and compared on common graphs using standard deviation error bars.

The first graph was of the first day's testing and has no delay introduced into the feedback. The following pages showcase the gain results for these same frequencies across the second, third, and fourth day of testing for each introduced delay. Tables show the values used to create the graphs.

Average Gain Responses, no delay, by day of testing

Gain Values, Day 01, no delay		
Frequency	**Avg Gain**	**Std. Dev.**
0.2	0.55	0.16
0.4	0.85	0.26
0.6	1.02	0.30
0.8	0.98	0.35
1	1.09	0.47

Table 3.5 Gain Values, Day 01, no delay

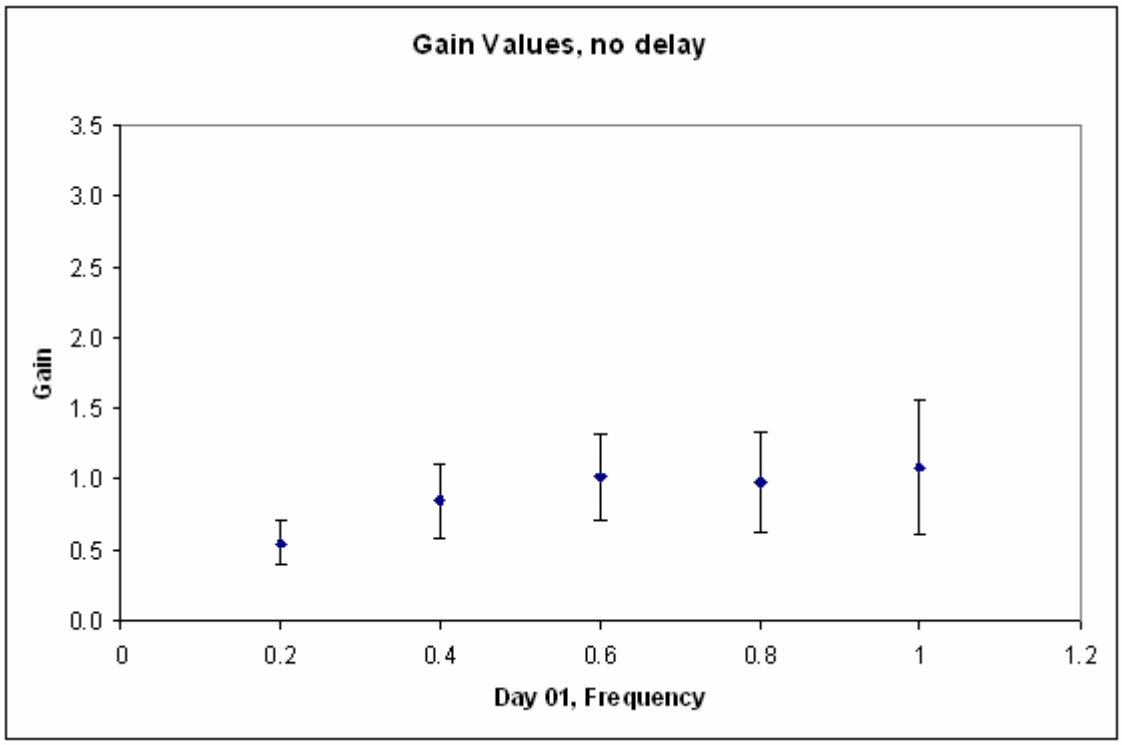

Figure 3.11 Gain Values by Frequency, Day 01, no delay

The gain response exhibited in Fig. 3.11, found in a slightly different manner than Fig. 3.7 (average of the gains, Fig 3.11, instead of the gain of the averaged data, Fig 3.7), reinforced the findings from above. With no delay, subjects showed gain responses that suggest successful tracking.

Average Gain Responses, 0.25 sec delay, by day of testing

0.2 Hz		
Gain Values, 0.25 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	0.94	0.52
Day 03	0.91	0.37
Day 04	0.74	0.36

0.4 Hz		
Gain Values, 0.25 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.39	0.46
Day 03	1.22	0.61
Day 04	1.12	0.59

0.6 Hz		
Gain Values, 0.25 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.23	0.80
Day 03	1.08	0.65
Day 04	0.98	0.60

0.8 Hz		
Gain Values, 0.25 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	0.94	0.46
Day 03	0.98	0.68
Day 04	0.92	0.53

1.0 Hz		
Gain Values, 0.25 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.32	0.99
Day 03	1.19	1.14
Day 04	1.09	0.63

Table 3.6 Gain Values, Days 02, 03, 04, 0.25 sec delay

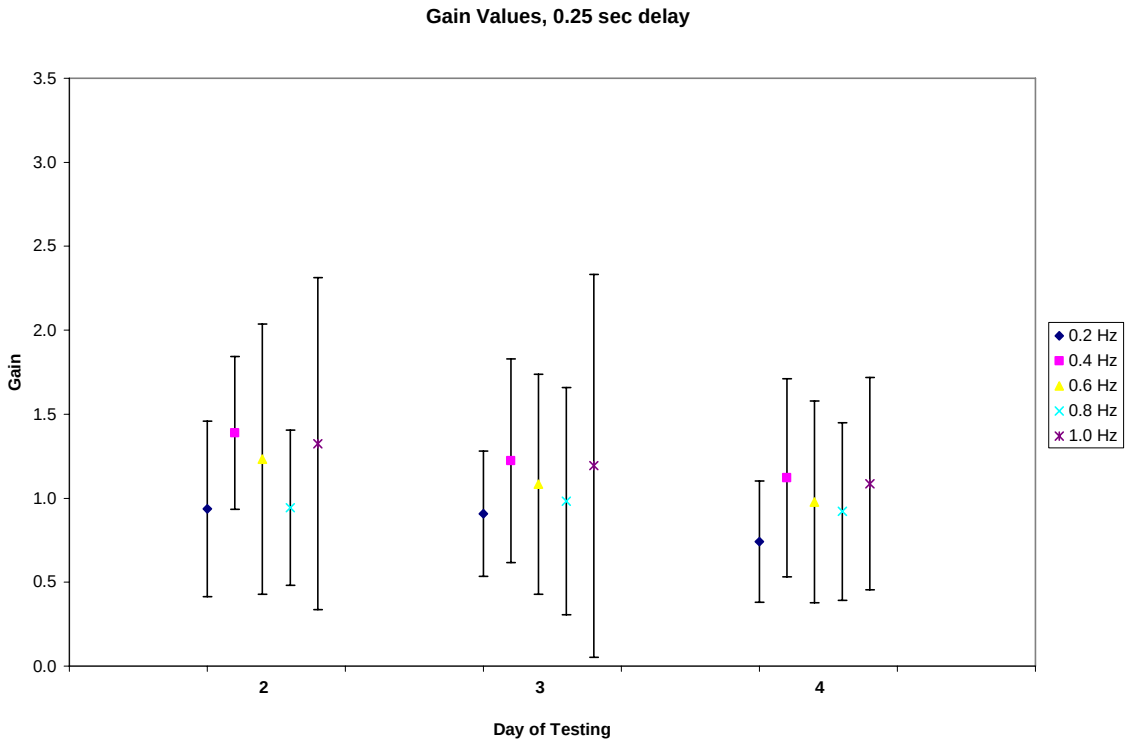

Figure 3.12 Gain Values by Frequency, Days 02-04, 0.25 sec delay

Average Gain Responses, 0.5 sec delay, by day of testing

0.2 Hz		
Gain Values, 0.5 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.11	0.72
Day 03	0.94	0.52
Day 04	0.78	0.38

0.4 Hz		
Gain Values, 0.5 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.19	0.66
Day 03	0.82	0.59
Day 04	0.86	0.46

0.6 Hz		
Gain Values, 0.5 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.09	0.68
Day 03	0.83	0.44
Day 04	0.90	0.58

0.8 Hz		
Gain Values, 0.5 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	0.97	0.55
Day 03	0.78	0.60
Day 04	0.81	0.52

1.0 Hz		
Gain Values, 0.5 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.29	0.92
Day 03	1.16	1.15
Day 04	1.03	0.74

Table 3.7 Gain Values, Days 02, 03, 04, 0.5 sec delay

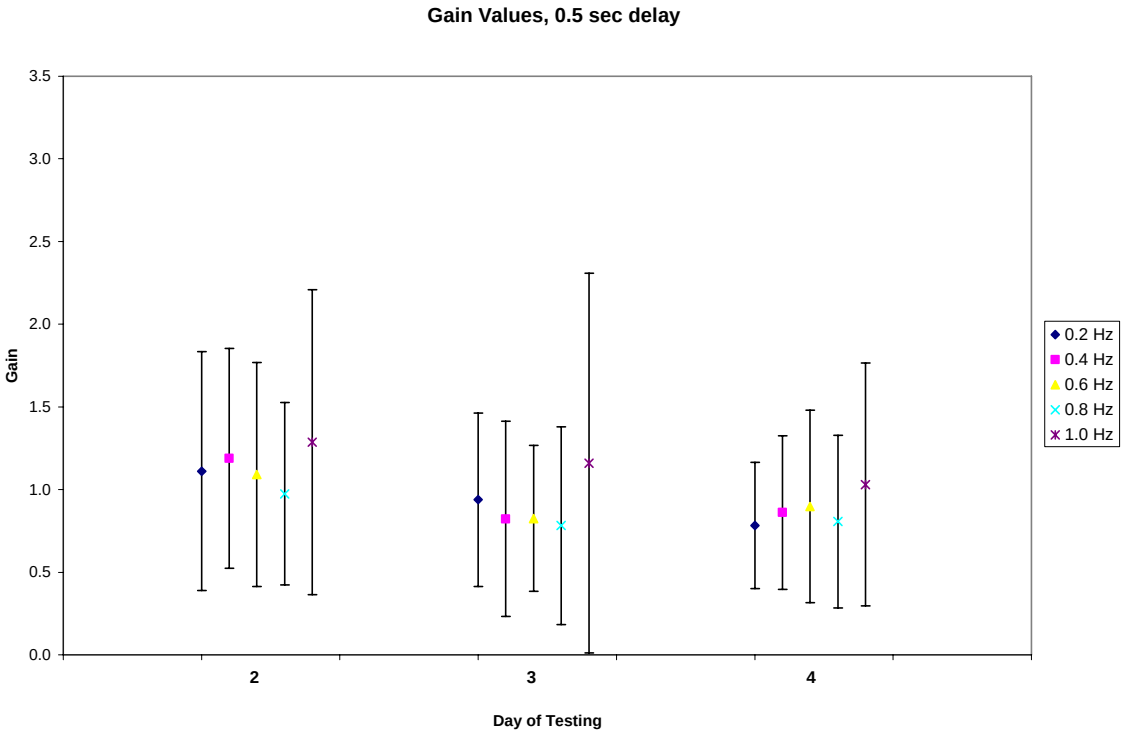

Figure 3.13 Gain Values by Frequency, Days 02-04, 0.5 sec delay

Average Gain Responses, 0.75 sec delay, by day of testing

0.2 Hz		
Gain Values, 0.75 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.49	0.91
Day 03	1.05	0.47
Day 04	0.96	0.45

0.4 Hz		
Gain Values, 0.75 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	0.65	0.40
Day 03	0.71	0.49
Day 04	0.64	0.29

0.6 Hz		
Gain Values, 0.75 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	0.61	0.44
Day 03	0.78	0.76
Day 04	0.66	0.51

0.8 Hz		
Gain Values, 0.75 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.04	0.55
Day 03	0.91	0.59
Day 04	0.90	0.60

1.0 Hz		
Gain Values, 0.75 sec delay, by day		
	Avg. Gain	Avg. Std Dev.
Day 02	1.91	1.34
Day 03	1.27	1.08
Day 04	1.28	0.83

Table 3.8 Gain Values, Days 02, 03, 04, 0.75 sec delay

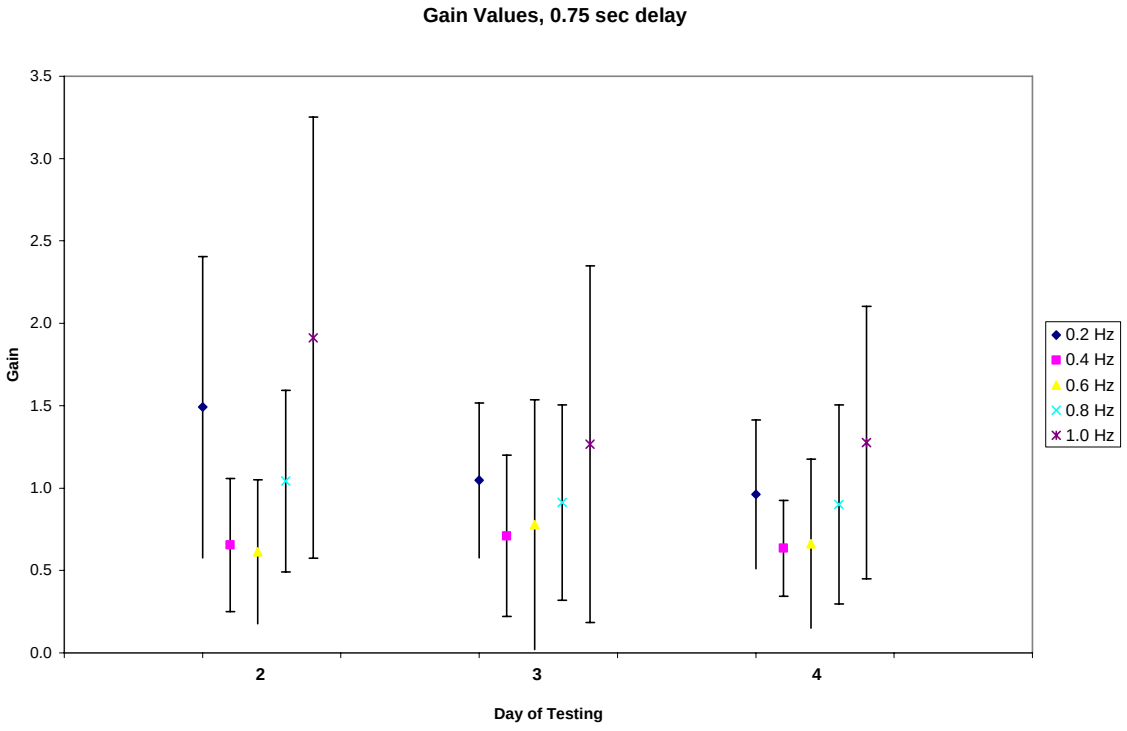

Figure 3.14 Gain Values by Frequency, Days 02-04, 0.75 sec delay

For each frequency presented with a feedback delay of 0.25 seconds, as seen in Fig 3.12, there appeared to be a general noticeable trend of a decreasing gain response as testing progressed. The 0.2 Hz stimulus frequency showed the lowest gain numbers, while 0.4 Hz showed the highest gain numbers. All but the 0.2 Hz stimulus frequency approached a gain of 1.0 as testing progressed. The 0.2 Hz stimulus actually began with a gain response of just below 1.0, but also decreased. Standard deviation of the gain values did not show a consistent trend across all frequencies and days of testing.

For each frequency presented with a feedback delay of 0.5 seconds, as seen in Fig 3.13, gain values showed less consistent change than with the delay set at 0.25 seconds. Although there seemed to be a general trend of a decreasing value, in some cases, values between consecutive days more or less remained the same. In those cases, variability decreased for all but one stimulus. There was an overall decrease in variability as subjects continued testing.

For each frequency presented with a feedback delay of 0.75 seconds, as with Fig 3.14, there was also a trend of a general decrease in gain response as days of testing continued. Variability decreased in three cases, but increased in two cases (0.6, 0.8 Hz). The lowest two stimulus frequencies (0.2 Hz, 0.4 Hz) showed a decrease in variability, as did the highest stimulus frequency (1.0 Hz).

Gain Values Averaged

In Table 3.9, gain values for all subject participants were averaged and their standard deviation calculated. Each delay value created a slightly different shaped gain distribution. For no delay, gain rose from 0.2 Hz to 0.6 Hz, where it peaked, and declined from 0.6 Hz to 1.0 Hz. With a 0.25 second delay, gain rose from 0.2 Hz to 0.4 Hz, and then declined from 0.4 Hz to 1.0 Hz. With the delay set at 0.50 seconds, gain peaked at 0.2 Hz, and declined until 0.8 Hz, before rising slightly at 1.0 Hz. For the largest delay, 0.75 seconds, gain peaked at 0.2 Hz and declined before rising at 0.8 Hz, and declined slightly at 1.0 Hz. These values were averaged across all days for trials where these frequencies were presented with these delays.

			Average Gain Values					
	Delay (sec)							
	0	0	0.25	0.25	0.5	0.5	0.75	0.75
	Avg Gain	Std Dev	Avg Gain	Std Dev	Avg Gain	Std Dev	Avg Gain	Std Dev
Freq. (Hz)								
0.2	0.55	0.11	0.74	0.21	0.83	0.32	1.01	0.37
0.4	0.84	0.16	1.13	0.31	0.67	0.30	0.32	0.25
0.6	1.03	0.21	0.79	0.32	0.31	0.18	0.22	0.10
0.8	0.93	0.30	0.30	0.17	0.25	0.17	0.55	0.35
1	0.69	0.32	0.27	0.13	0.46	0.33	0.49	0.29
Random	0.98	0.53	0.63	0.46	1.10	1.18	1.19	0.75

Table 3.9 Average Gain Values for all Days, from all Data, based on Frequency and Delay

Phase Responses

To attempt to compare stimulus and response in a way that allowed us to quantify the relationship and try to show if participants were able to improve their performance, we chose to calculate the phase response. However, to compare a phase response in the time domain, it was important to compare the position in space of both the target and response vectors on the screen at similar times. The best way to quantify this was to compare when the target and response icons crossed the midline of the monitor in front of the subjects.

For higher frequency stimuli, there were more midline crossings to compare. As can be seen in the graphs to the right, with all stimuli, subjects were able to track their target accurately. The difference in their midline crossings times was approximately zero throughout the tests that were conducted without an introduced feedback delay. For higher frequency stimuli, the phase differences exhibited a smaller variability than the lower frequency tests. For Fig 3.15 – 3.20, the vertical axis is a unit of time, in centiseconds.

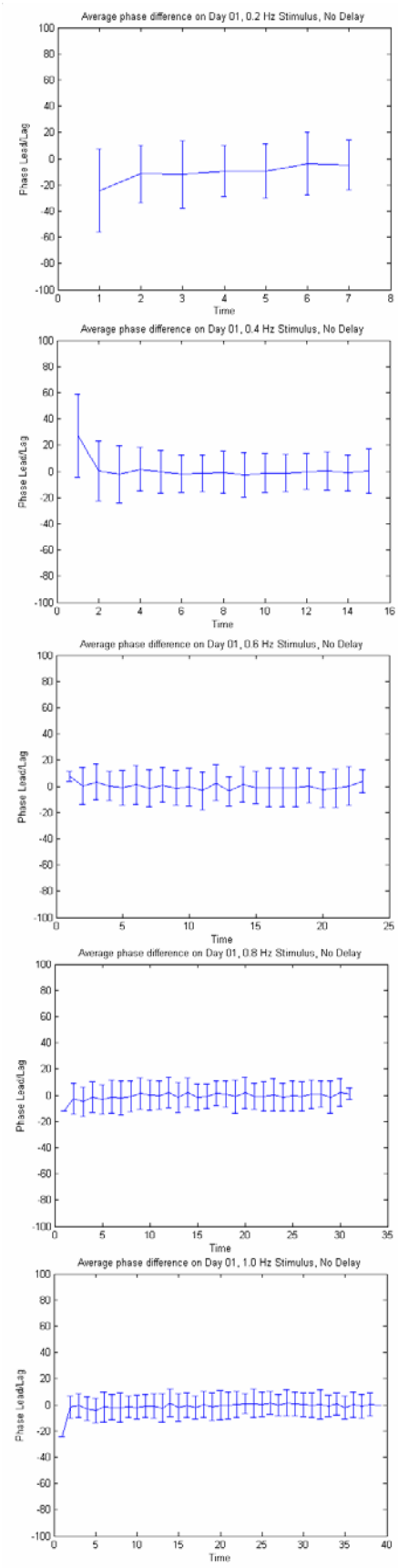

Figure 3.15 Phase Differences, Day 01

Phase responses for 0.2 Hz stimulus

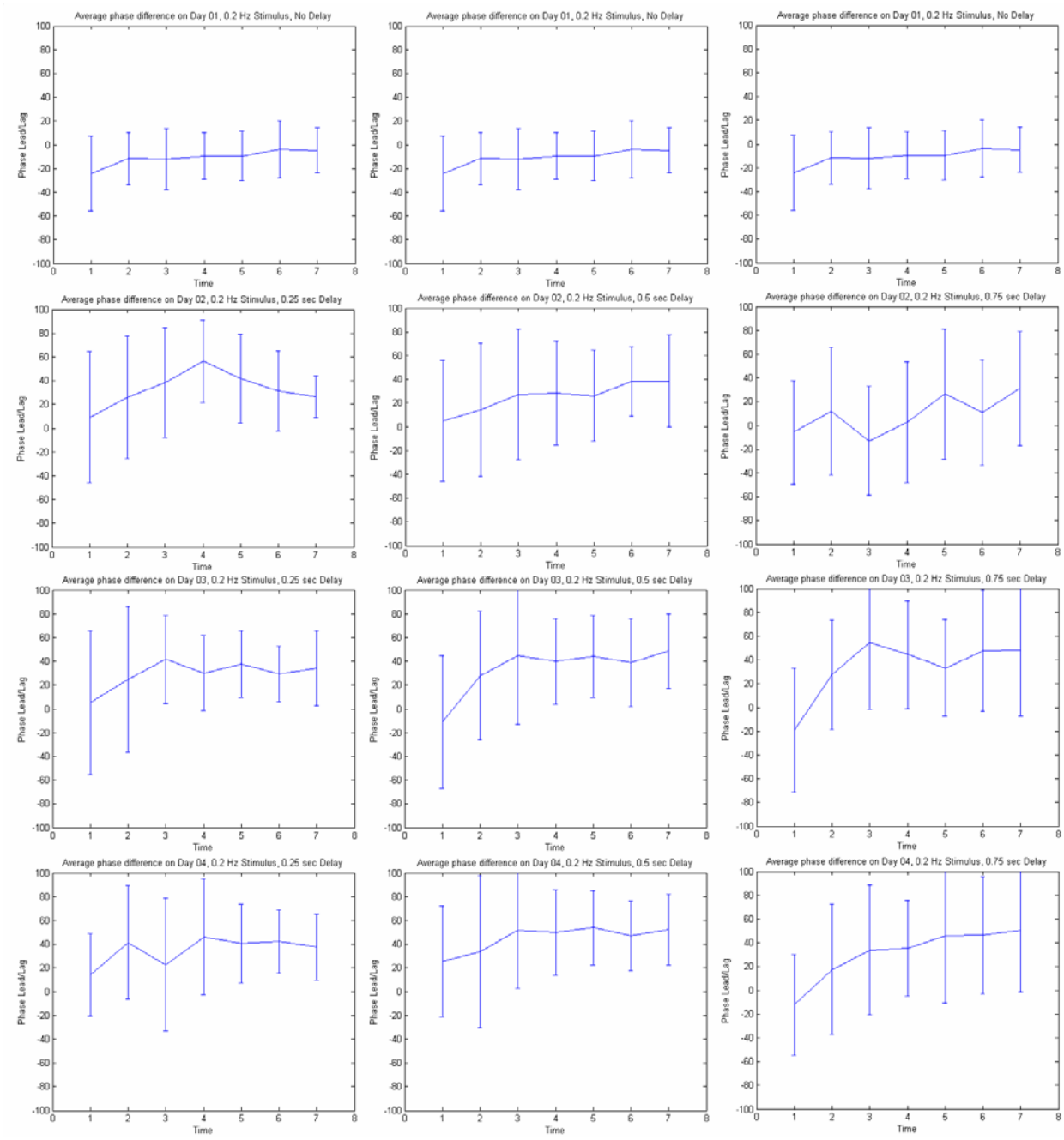

Figure 3.16 Phase Differences, Days 02-04
0.2 Hz
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

Phase responses for 0.4 Hz stimulus

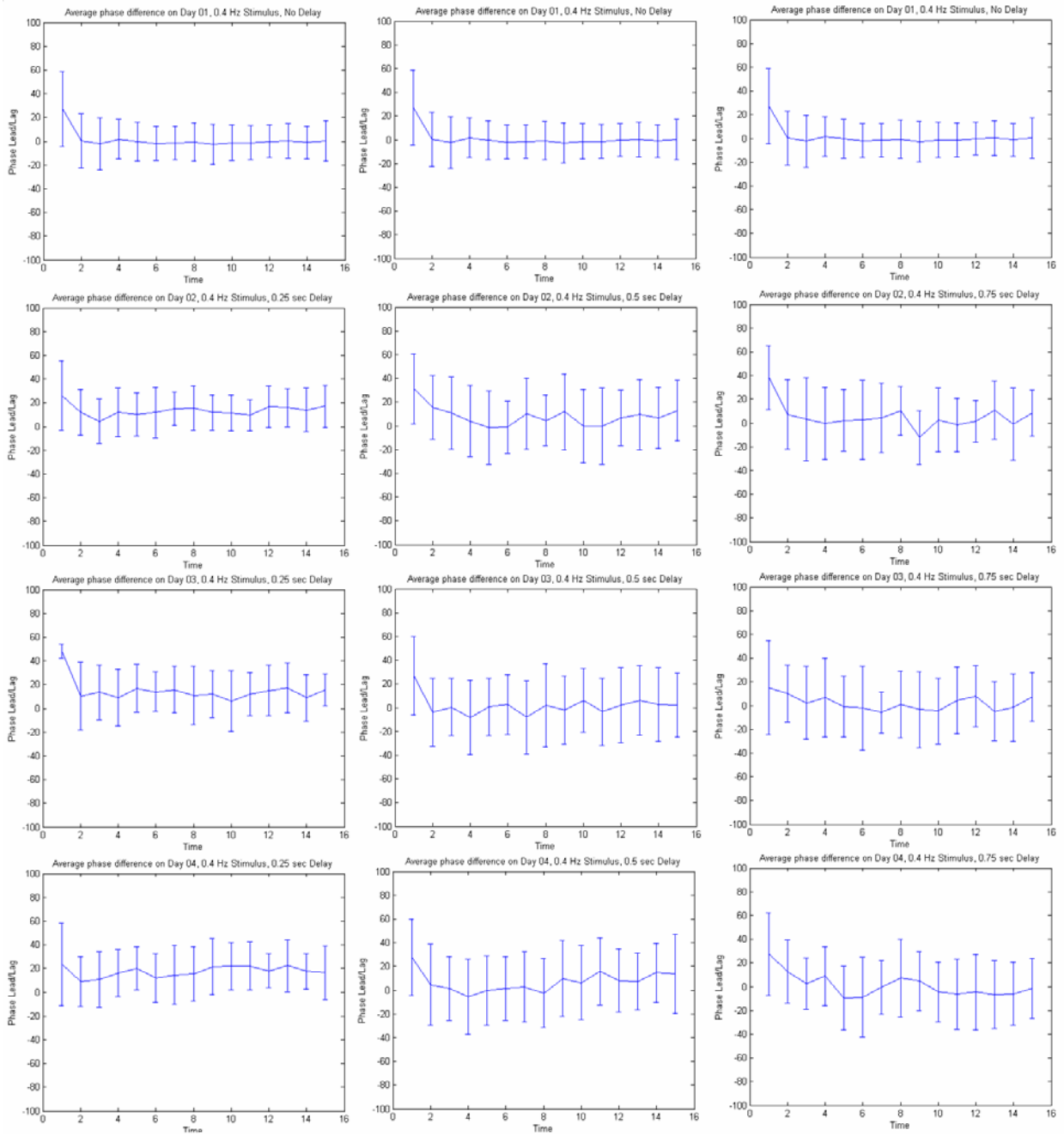

Figure 3.17 Phase Differences, Days 02-04
0.4 Hz
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

Phase responses for 0.6 Hz stimulus

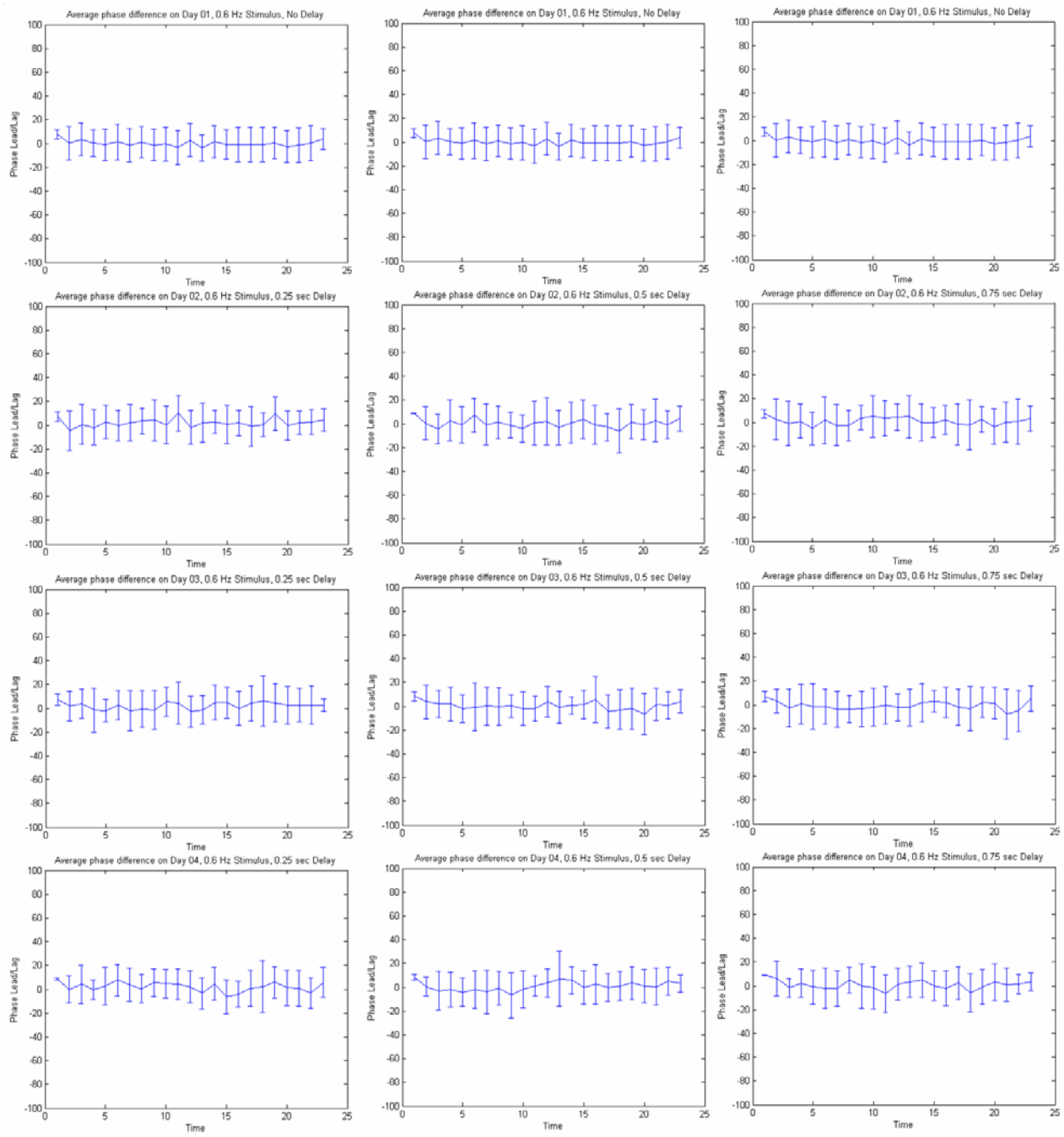

Figure 3.18 Phase Differences, Days 02-04
0.6 Hz
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

Phase responses for 0.8 Hz stimulus

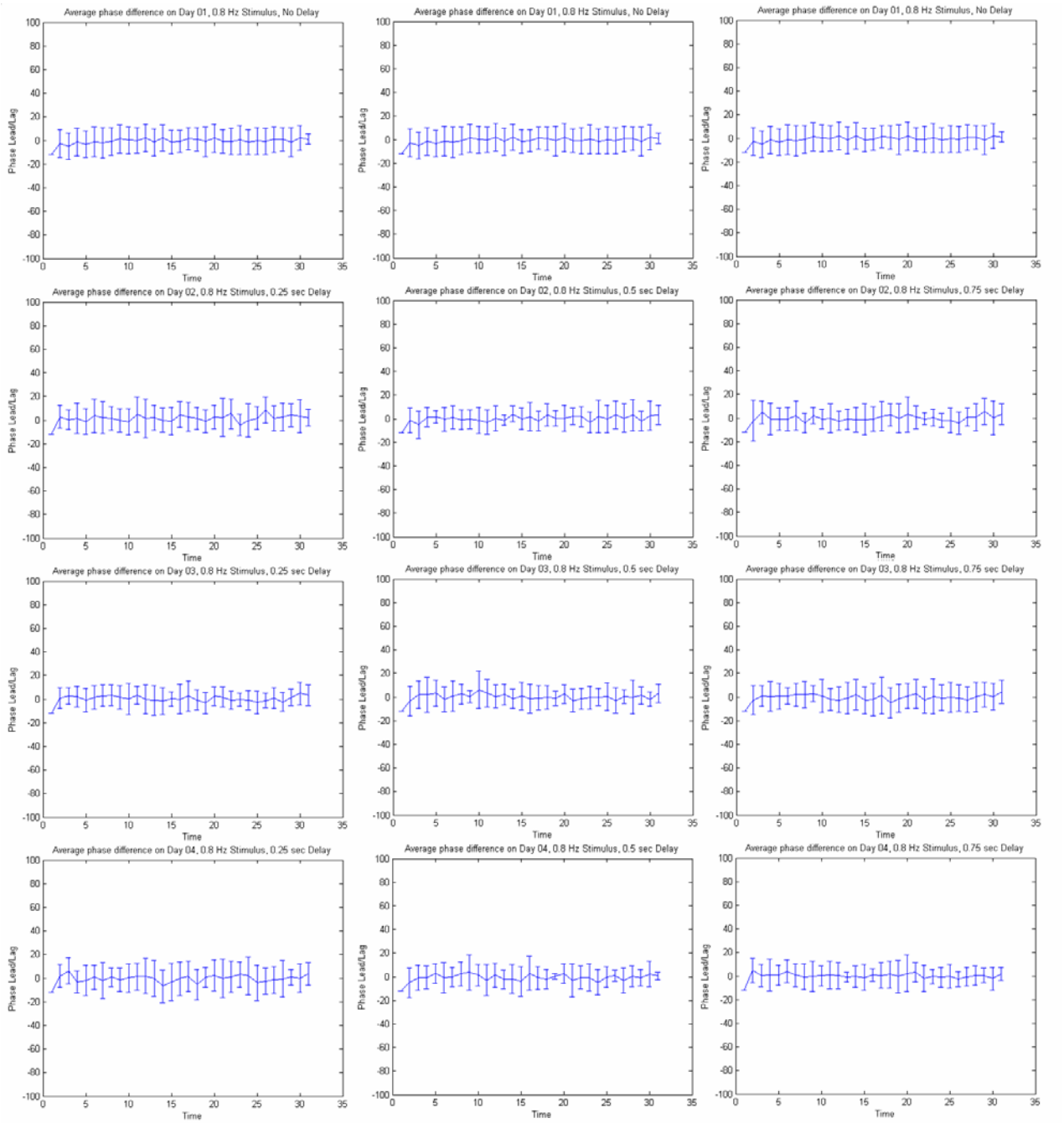

Figure 3.19 Phase Differences, Days 02-04
0.8 Hz
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

Phase responses for 1.0 Hz stimulus

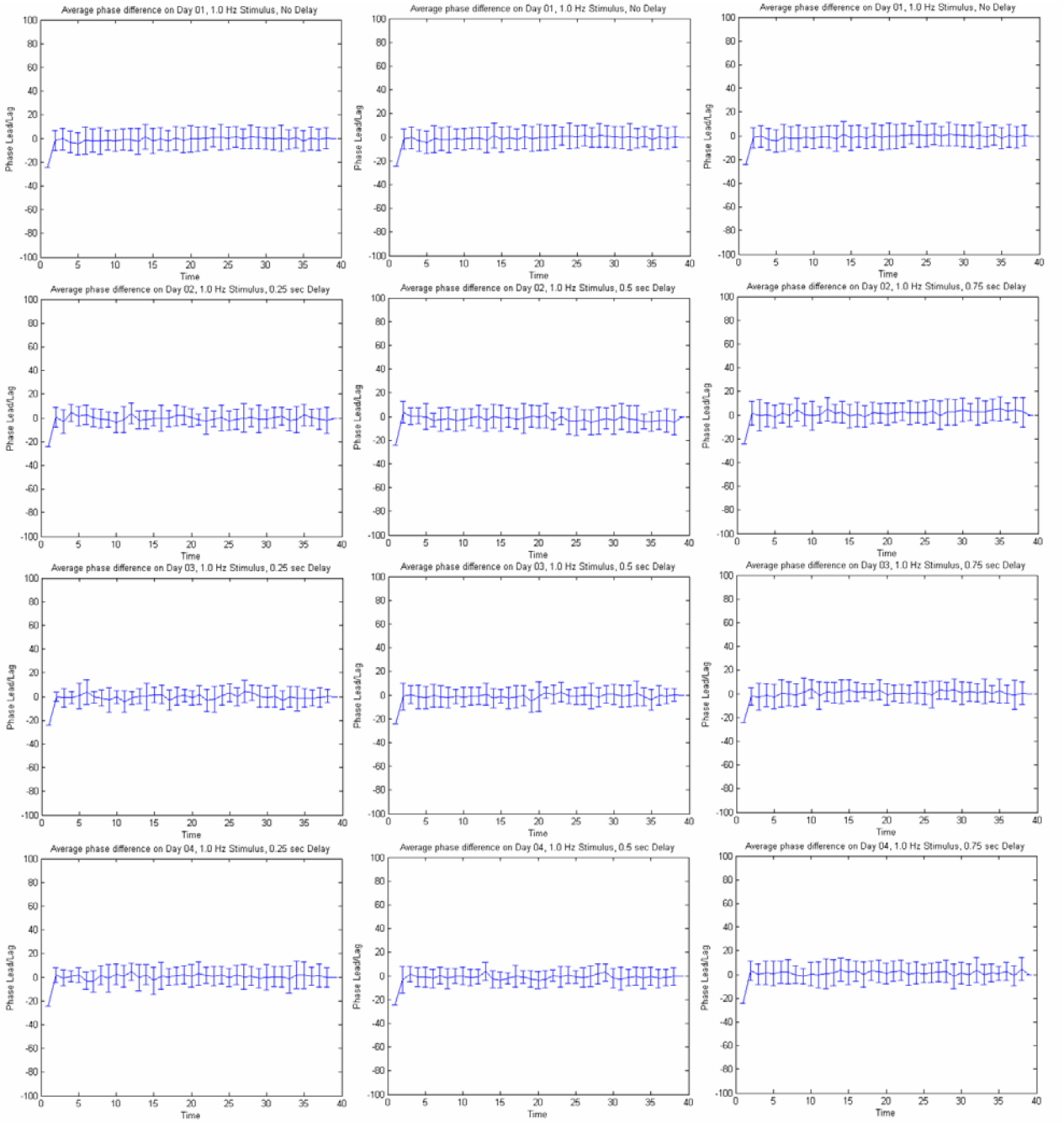

Figure 3.20 Phase Differences, Days 02-04
1.0 Hz
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

The above pages highlighted the phase differences between stimuli and response for each frequency presented to study participants. Each page above contains the phase response graphs for each frequency in sequential increasing order. Each row from top to bottom shows the progression from Day 01 through Day 04. The leftmost column shows the responses to a 0.25 second delay, the middle column shows the responses to a 0.5 second delay, and the right-hand column shows the responses to the 0.75 second delay. As the frequency was increased, the phase lag/lead became closer to zero and the variability decreased.

As with the gain evaluation, it was critical to view the phase responses on the same scale to allow easier comparisons. The following graphs show phase lag/lead responses based on which delay was introduced into their feedback. For Day 01, 0.2 Hz stimulus, it should be noted that this was the first trial attempt for all participants, and therefore its values may be skewed due to learning the program at the beginning of testing.

Average Phase Values, no delay, by day of testing

Phase Values, Day 01, no delay		
Frequency	**Avg. Phase lag/lead**	**Std Dev.**
0.2	-10.75	23.22
0.4	1.16	17.22
0.6	0.17	12.99
0.8	-0.81	10.58
1	-1.27	9.00

Table 3.10 Phase Values, Day 01, no delay

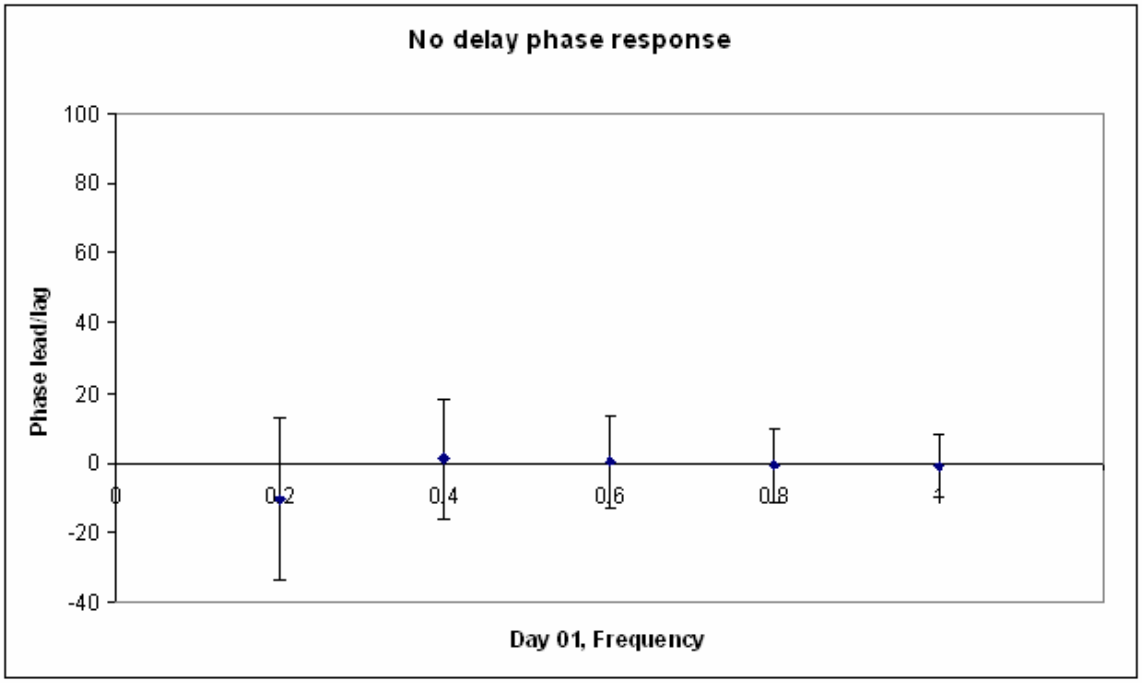

Figure 3.21 Phase Lag Values by Frequency, Day 01, no delay

Looking at the above data, 0.2 Hz stimuli on the first day of testing yielded an average phase lag of approximately -10.7 csec, which translated to a lag of almost .11 seconds. That lag would be approximately 7.9 degrees. The other frequencies created a lag closer to zero, and exhibited less variability than the 0.2 Hz stimulus.

Average Phase Values, 0.25 sec delay, by day of testing

	Phase Values, Days 02-04, 0.25 second delay					
Frequency	**Day 02**		**Day 03**		**Day 04**	
	Avg. Phase	**Std Dev.**	**Avg. Phase**	**Std Dev.**	**Avg. Phase**	**Std Dev.**
0.2	32.75	39.54	29.10	39.15	34.95	39.35
0.4	13.54	18.24	15.00	20.15	17.46	21.55
0.6	2.05	13.21	2.08	13.89	2.08	13.01
0.8	1.34	11.01	0.20	8.83	-0.62	11.91
1	-0.89	8.09	-0.83	7.40	0.06	8.25

Table 3.11 Phase Values, Days 02-04, 0.25 sec delay

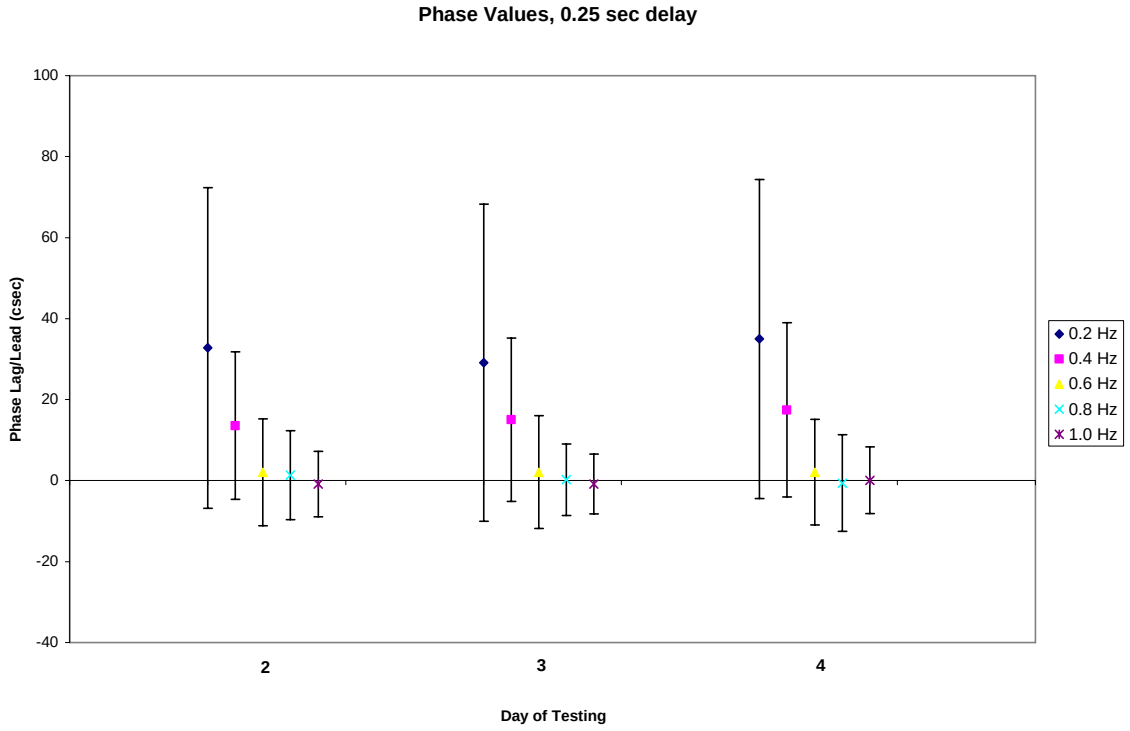

Figure 3.22 Phase Lag Values by Frequency, Days 02-04, 0.25 sec delay

With a 0.25 second delay, the lower frequency stimuli produced a phase lead. With lower frequency stimuli, study participants were able to lead the target, whereas the higher frequency stimuli showed average phase leads around zero.

Average Phase Values, 0.5 sec delay, by day of testing

	Phase Values, Days 02-04, 0.5 second delay					
Frequency	**Day 02**		**Day 03**		**Day 04**	
	Avg. Phase	**Std Dev.**	**Avg. Phase**	**Std Dev.**	**Avg. Phase**	**Std Dev.**
0.2	25.38	44.61	33.25	43.78	44.90	40.97
0.4	8.01	28.05	1.74	29.04	7.07	29.33
0.6	0.48	14.22	0.41	13.34	0.72	13.28
0.8	-0.07	9.22	-0.06	9.67	-0.84	9.50
1	-2.38	8.91	-1.36	7.91	-1.51	7.07

Table 3.12 Phase Values, Days 02-04, 0.5 sec delay

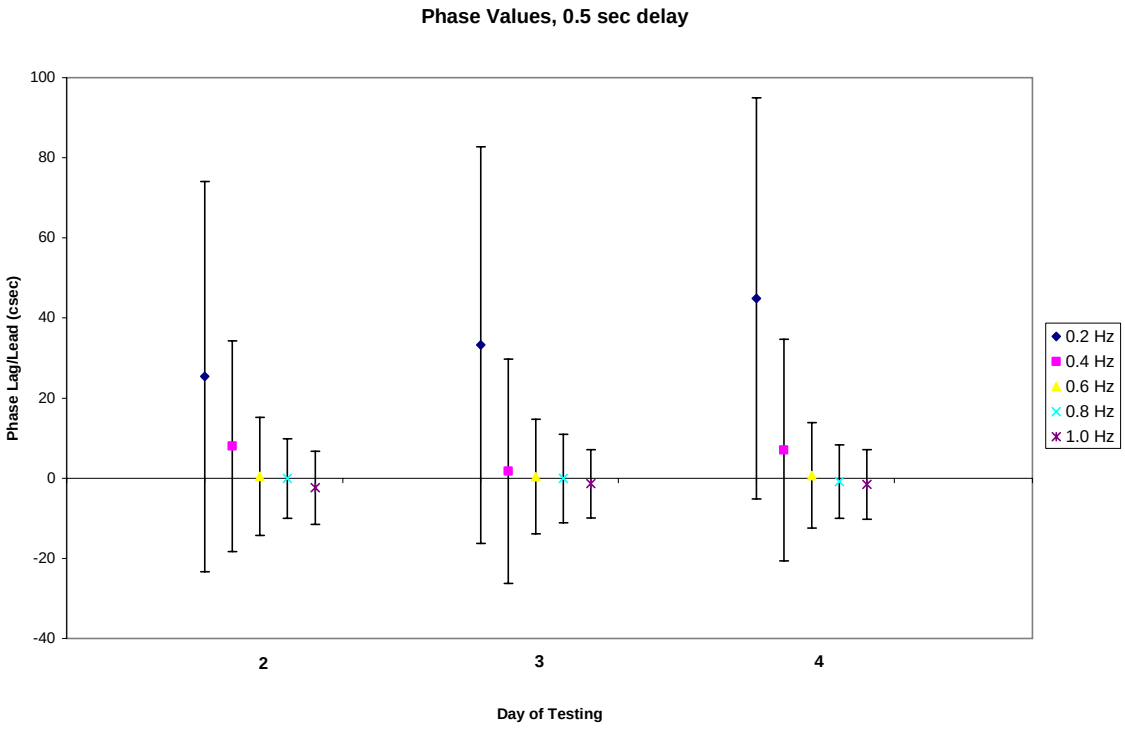

Figure 3.23 Phase Lag Values by Frequency, Days 02-04, 0.5 sec delay

With the introduced delay increased to 0.5 seconds, subjects were not able to sufficiently lead the target to match their onscreen icon. However, subjects were able to lead the target for the 0.2 Hz frequency stimulus, but with large variability. Frequencies higher than 0.2 Hz showed values around zero, but 0.4 Hz showed some phase leading.

Average Phase Values, 0.75 sec delay, by day of testing

	Phase Values, Days 02-04, 0.75 second delay					
Frequency	**Day 02**		**Day 03**		**Day 04**	
	Avg. Phase	**Std Dev.**	**Avg. Phase**	**Std Dev.**	**Avg. Phase**	**Std Dev.**
0.2	9.16	48.72	33.89	49.49	31.08	50.10
0.4	5.14	26.30	2.13	28.04	1.07	27.64
0.6	1.11	14.74	-0.65	14.31	0.79	13.14
0.8	-0.37	9.92	-0.47	11.08	-0.04	9.17
1	1.17	9.13	0.07	8.53	0.76	8.67

Table 3.13 Phase Values, Days 02-04, 0.75 sec delay

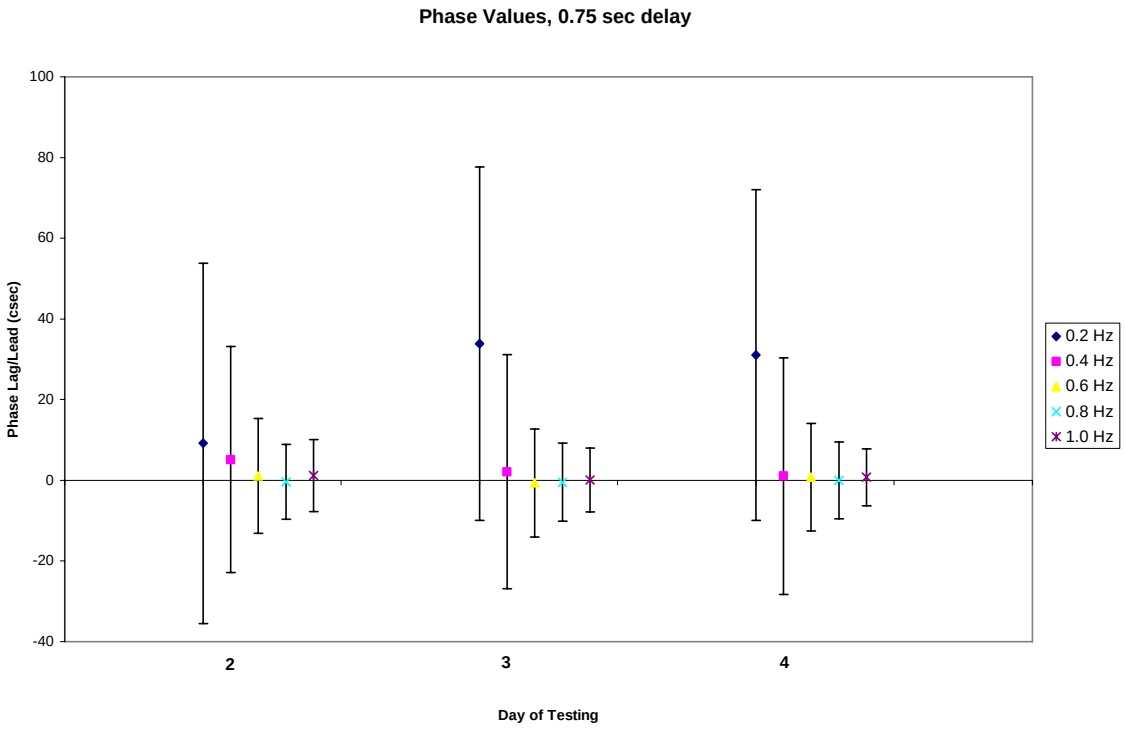

Figure 3.24 Phase Lag Values by Frequency, Days 02-04, 0.75 sec delay

With the introduced delay increased to 0.75 seconds, subjects were not able to sufficiently lead the target to match their onscreen icon. On days 03 and 04, subjects were able to lead the target for the 0.2 Hz frequency stimulus, but with large variability. Frequencies higher than 0.2 Hz showed difficulty tracking their targets.

Midline Crossing Matches

As mentioned earlier, to find the phase response of study participants, we found the places where the target and the subject icons crossed the midline on the monitor in front of the subjects. However, there were incidences where a subject was unable to keep up with the target or hesitated, which resulted in a different number of midline crossings for stimulus and response. In those cases, it was impossible to match up directly for some particular stimulus midline crossings. That comparison, which was unable to be made, was thrown out. The following data shows how successful participants were at crossing the midline within a half cycle of the crossing by the stimulus. Table 3.14 shows the percentage of midline crossings that were successfully matched on Day 01, with no delay presented. Table 3.15 shows the percentage of midline crossings that were successfully matched for all days, organized by delay.

It should be noted that Day 01 values for Table 3.15 had no delay presented.

Percentage of Matched Crossings

Percentage of Crossings Matched		
	No delay	
Frequency	**Day 01**	
0.2	99.35	
0.4	98.08	
0.6	58.56	
0.8	74.24	
1	71.21	

Table 3.14 Percentages of Midline Crossings Matched by All Participants

	Percentage of Crossings Matched			
		0.25 sec delay		
Frequency	**Day 01**	**Day 02**	**Day 03**	**Day 04**
0.2	99.35	90.91	92.86	92.86
0.4	98.08	96.67	95.45	96.67
0.6	58.56	46.44	47.83	38.74
0.8	74.24	48.83	31.82	42.67
1	71.21	45.93	39.00	40.79
	Percentage of Crossings Matched			
		0.5 sec delay		
Frequency	**Day 01**	**Day 02**	**Day 03**	**Day 04**
0.2	99.35	94.16	93.51	94.16
0.4	98.08	84.55	82.12	97.27
0.6	58.56	50.99	43.48	46.25
0.8	74.24	41.79	40.91	39.15
1	71.21	56.34	43.06	40.67
	Percentage of Crossings Matched			
		0.75 sec delay		
Frequency	**Day 01**	**Day 02**	**Day 03**	**Day 04**
0.2	99.35	87.66	93.51	88.96
0.4	98.08	78.18	72.12	94.85
0.6	58.56	50.99	48.02	41.11
0.8	74.24	54.69	54.69	42.52
1	71.21	59.33	55.62	54.07

Table 3.15 Percentages of Midline Crossings Matched by All Participants

Random Stimuli

In an attempt to provide a control group to compare the results of the experiment, the study participants were presented with a random stimulus randomly mixed in with the previously mentioned stimulus frequencies. The random stimulus was actually a composite of the sum of three frequencies, 0.3 Hz, 0.8 Hz, and 1.6 Hz. Although the stimulus was a sum of sines, the movements appeared nonperiodic, and therefore were unpredictable.

As such, it was important to analyze the gain response of the individual frequencies to determine if the study participants were able to react to the random stimulus. By analyzing gain responses of each frequency within the random stimulus, we were able to determine if the subjects reacted more effectively to lower or higher frequencies within the random stimulus.

The phase response associated with the random stimulus was also analyzed, with no reference to embedded stimulus frequencies.

Examining the random stimulus separately allowed us to break down the stimulus into its frequency parts. As mentioned earlier, the random stimulus was actually a sum of sines, consisting of 0.3 Hz, 0.8 Hz, and a 1.6 Hz waves. We looked for frequency responses at the lower, middle, and higher frequency.

Average Gain Response, Random Stimulus, by delay

	Gain Values, Random Stimulus			
	Delay			
Frequency	**0.00 sec**	**0.25 sec**	**0.50 sec**	**0.75 sec**
0.3 Hz	0.03	0.02	0.06	0.03
0.8 Hz	0.06	0.02	0.03	0.02
1.6 Hz	0.71	0.3	0.28	0.38

Table 3.16 Gain Values by Delay for Random stimulus

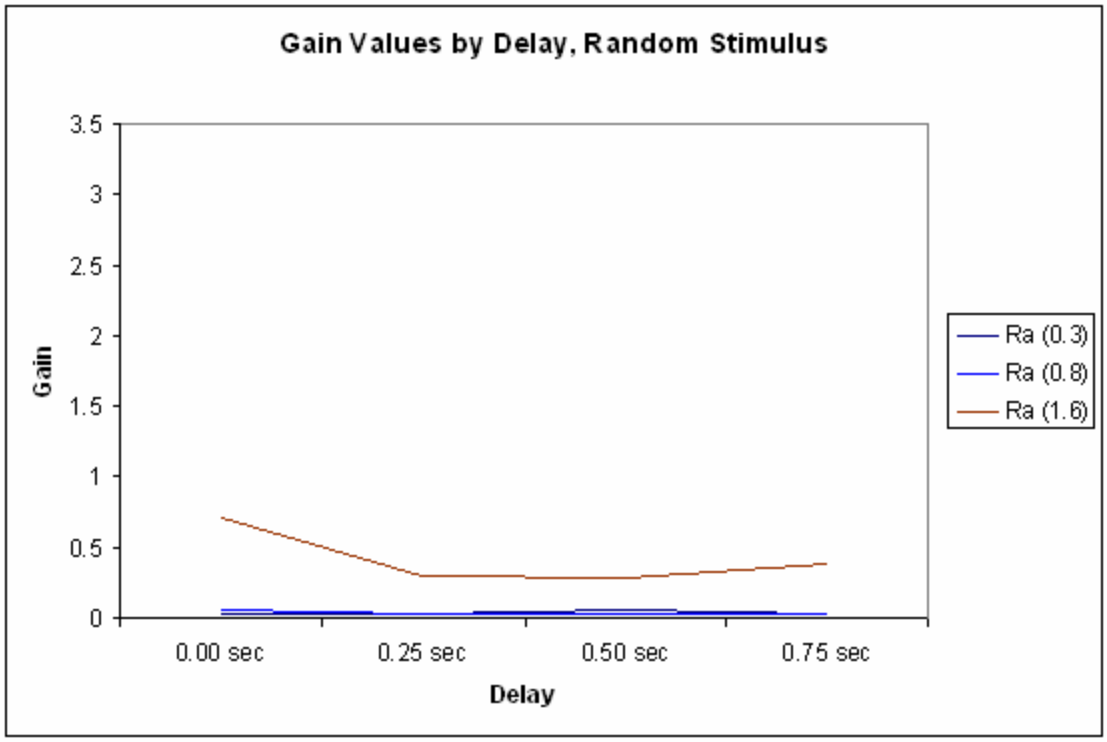

Figure 3.25 Gain Values by Delay for Random stimulus

When we looked at gain responses for the random stimulus, it quickly became apparent that subjects were much more easily able to track the high frequency. Within the high frequency, though, an introduced delay caused a significant drop in gain response, but with some small improvement with the largest delay.

Average Gain Response, Random Stimulus, no delay, by day

Gain Response, Random Stimulus		
	No delay	
Day 01	**Avg. Gain**	**Std. Dev.**
Ra (0.3)	0.18	0.22
Ra (0.8)	0.15	0.14
Ra (1.6)	1.19	0.89

Table 3.17 Gain Values, Random Stimulus, by Frequency, no delay

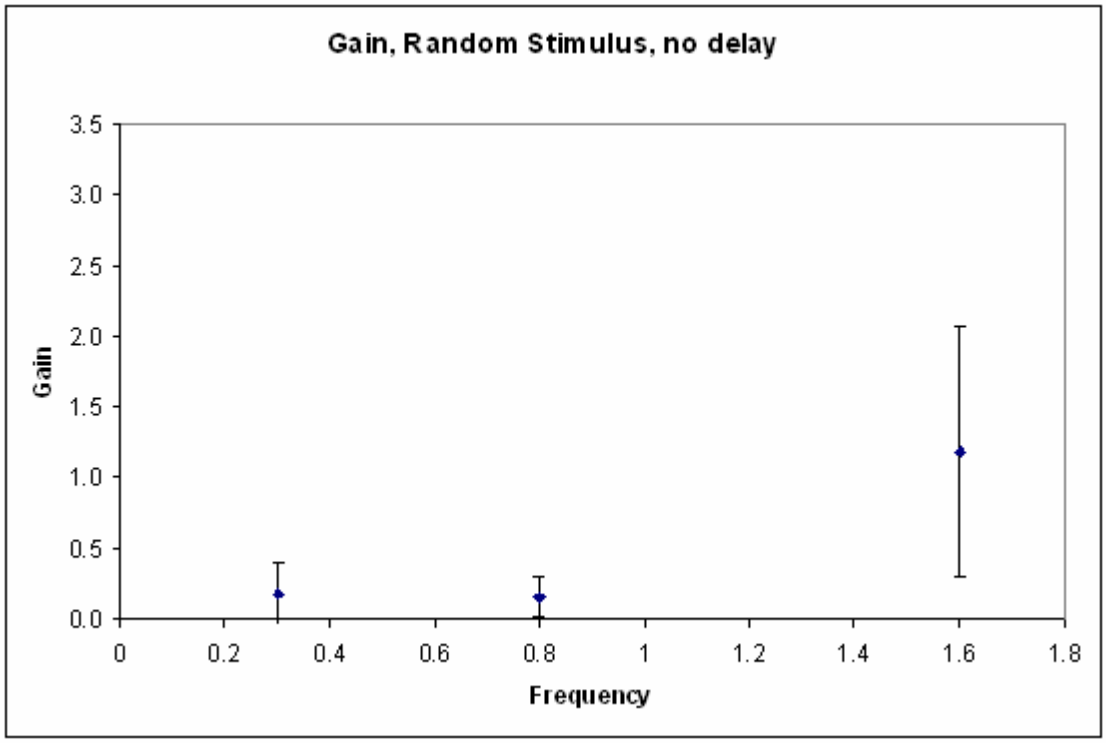

Figure 3.26 Gain Values, Random Stimulus, no delay

This clearly indicated that of the characteristic frequencies in the random stimulus, subjects were more easily able to track the highest frequency of 1.6 Hz. Although variability was higher, the gain average for 1.6 Hz was close to one, while the other two frequencies were close to zero.

Average Gain Response, Random Stimulus, 0.25 sec delay, by day

		Gain Responses, Random Stimulus						
			0.25 sec delay					
Day 02	**Avg. Gain**	**Std. Dev.**	**Day 03**	**Avg. Gain**	**Std. Dev.**	**Day 04**	**Avg. Gain**	**Std. Dev.**
Ra (0.3)	0.31	0.38	**Ra (0.3)**	0.53	0.60	**Ra (0.3)**	0.59	0.76
Ra (0.8)	0.33	0.32	**Ra (0.8)**	0.37	0.45	**Ra (0.8)**	0.29	0.36
Ra (1.6)	1.62	2.22	**Ra (1.6)**	0.80	0.55	**Ra (1.6)**	0.71	1.01

Table 3.18 Gain Values, Random Stimulus, 0.25 sec delay

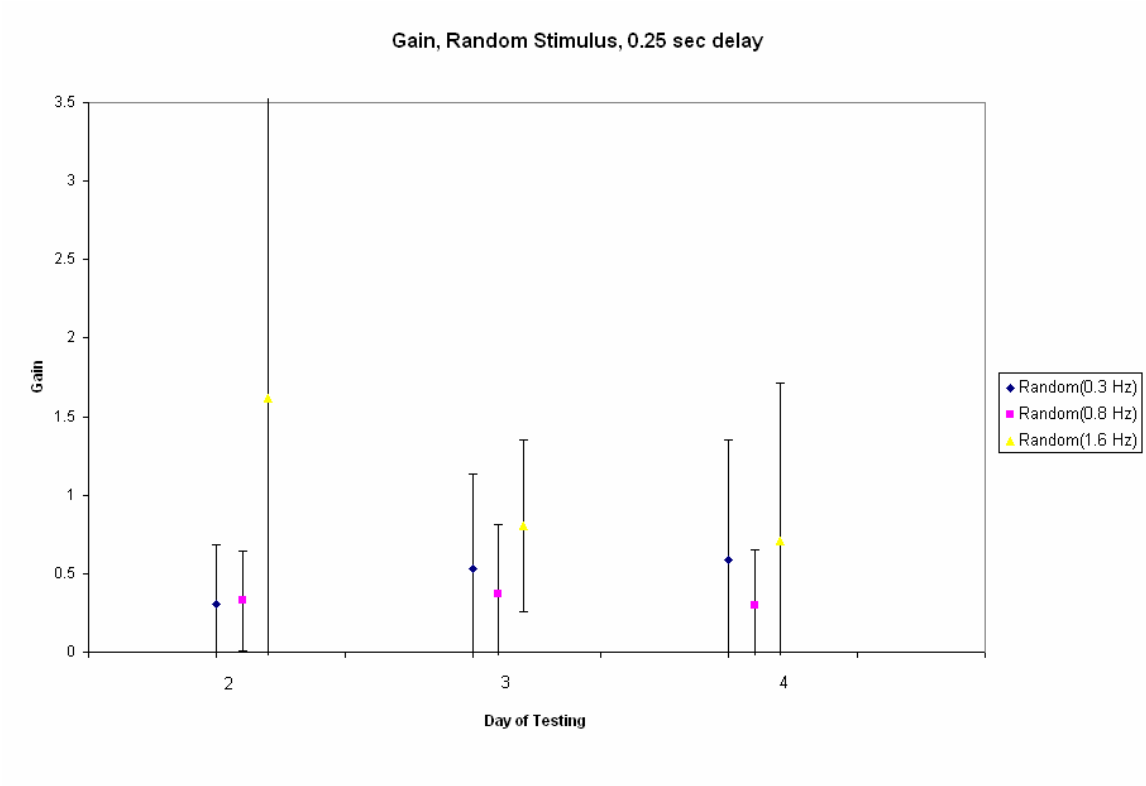

Figure 3.27 Gain Values, Random Stimulus, 0.25 sec delay

Results from the gain analysis of the random stimulus presented with a 0.25 second delay corroborated the gain response seen with no delay added into the feedback loop.

Average Gain Response, Random Stimulus, 0.5 sec delay, by day

		Gain Responses, Random Stimulus						
			0.5 sec delay					
Day 02	**Avg. Gain**	**Std. Dev.**	**Day 03**	**Avg. Gain**	**Std. Dev.**	**Day 04**	**Avg. Gain**	**Std. Dev.**
Ra (0.3)	0.63	0.97	**Ra (0.3)**	0.59	0.64	**Ra (0.3)**	0.72	1.01
Ra (0.8)	0.54	0.94	**Ra (0.8)**	0.41	0.53	**Ra (0.8)**	0.83	2.17
Ra (1.6)	0.84	0.89	**Ra (1.6)**	0.83	1.02	**Ra (1.6)**	0.51	0.61

Table 3.19 Gain Values, Random Stimulus, 0.5 sec delay

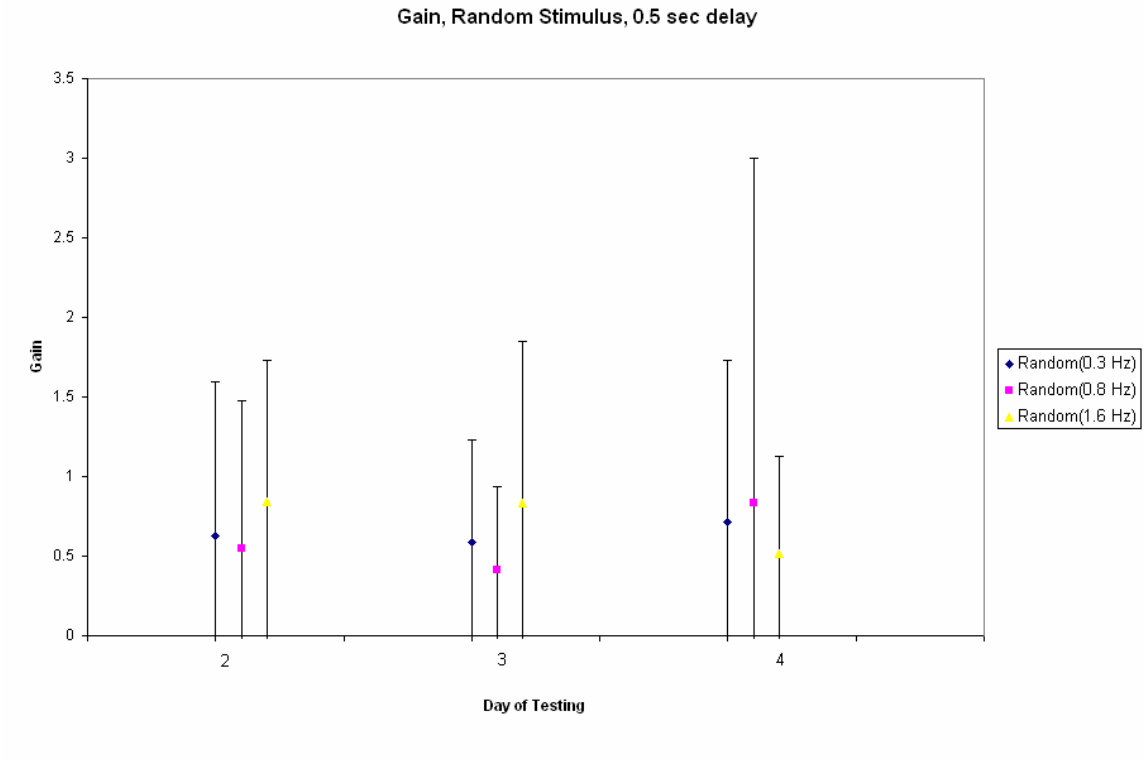

Figure 3.28 Gain Values, Random Stimulus, 0.5 sec delay

Again, with the feedback delay increased to 0.5 seconds, the highest frequency seemed to have the gain response closest to one. On Day 04, the two lower frequencies showed an increase in gain, while the highest stimulus frequency decreased.

Average Gain Response, Random Stimulus, 0.75 sec delay, by day

		Gain Responses, Random Stimulus						
			0.75 sec delay					
Day 02	**Avg. Gain**	**Std. Dev.**	**Day 03**	**Avg. Gain**	**Std. Dev.**	**Day 04**	**Avg. Gain**	**Std. Dev.**
Ra (0.3)	0.56	0.62	**Ra (0.3)**	0.59	0.63	**Ra (0.3)**	0.57	0.82
Ra (0.8)	0.20	0.26	**Ra (0.8)**	0.36	0.47	**Ra (0.8)**	0.76	2.23
Ra (1.6)	1.12	1.12	**Ra (1.6)**	0.84	1.07	**Ra (1.6)**	0.90	1.11

Table 3.20 Gain Values, Random Stimulus, 0.75 sec delay

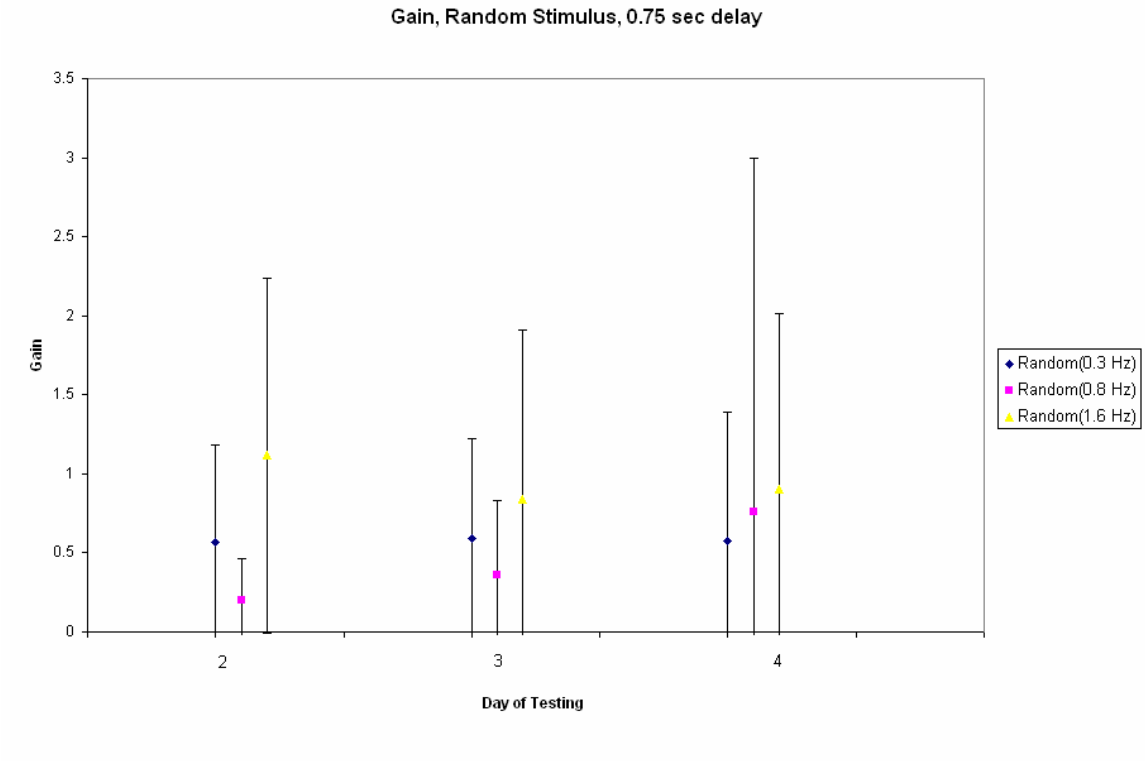

Figure 3.29 Gain Values, Random Stimulus, 0.75 sec delay

With the feedback delay increased to 0.75 seconds, the highest (1.6 Hz) stimulus frequency again showed a gain response closest to one, with no real change in the lowest frequency, and a moderate improvement by Day 04 in the mid-range frequency.

Random Phase Response

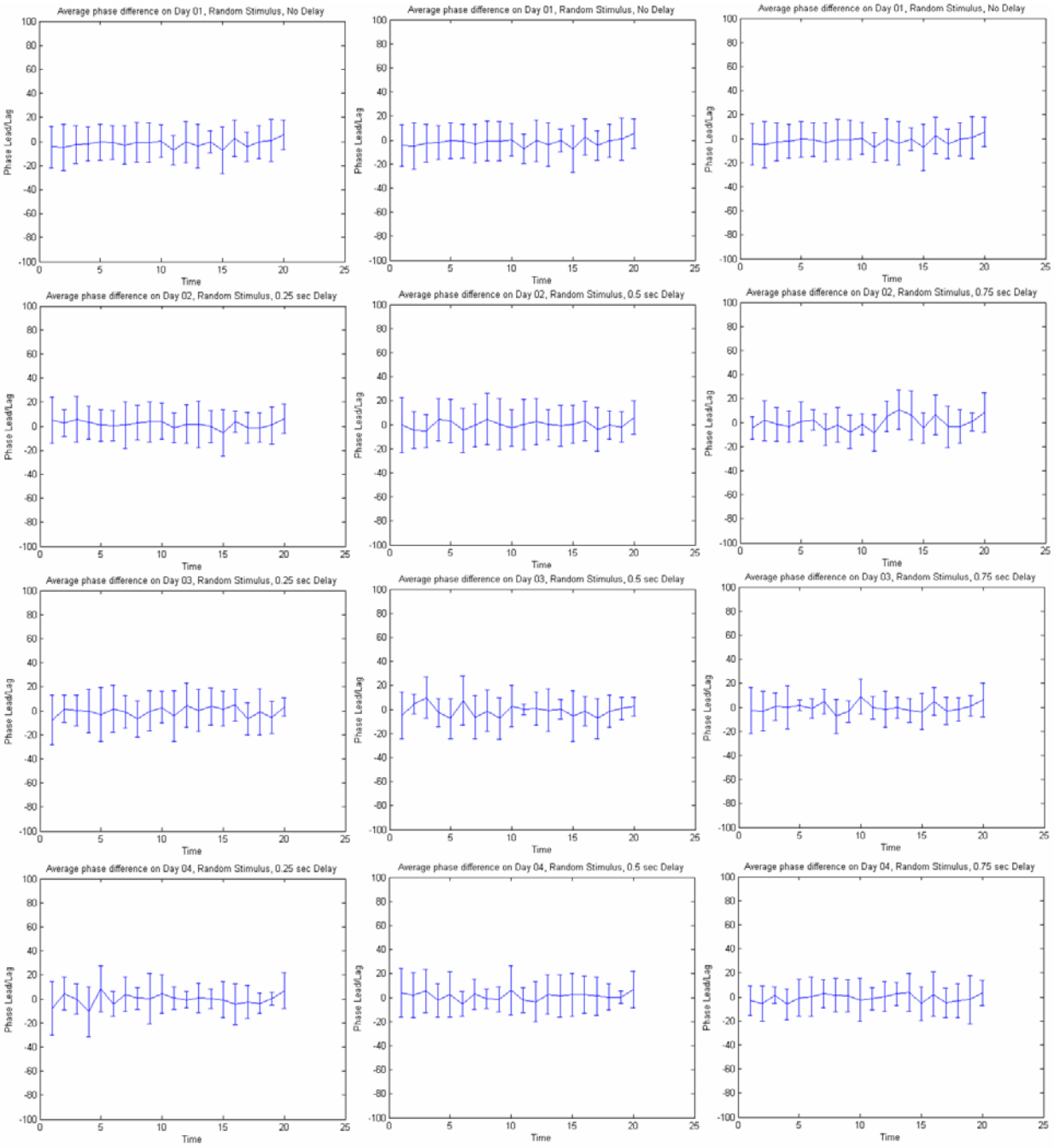

Figure 3.30 Phase Differences, Days 02-04
Random Stimulus
a. 0.25 sec delay b. 0.50 sec delay c. 0.75 sec delay

As with the gain, the phase response of the random stimulus presentation was analyzed as a control to compare against the other stimulus frequencies.

			Phase Responses, Random Stimulus					
Delay	**Day01**		**Day 02**		**Day 03**		**Day 04**	
(sec)	***Avg. Gain***	***Std. Dev.***	***Avg. Gain***	***Std. Dev.***	***Avg. Gain***	***Std. Dev.***	***Avg. Gain***	***Std. Dev.***
0	-1.78	15.27						
0.25			1.64	14.80	-0.58	15.89	-0.14	13.51
0.5			0.06	17.01	-0.92	14.42	1.30	14.67
0.75			-0.15	13.83	-0.12	11.96	-0.85	13.60

Table 3.21 Phase Values, Random Stimulus

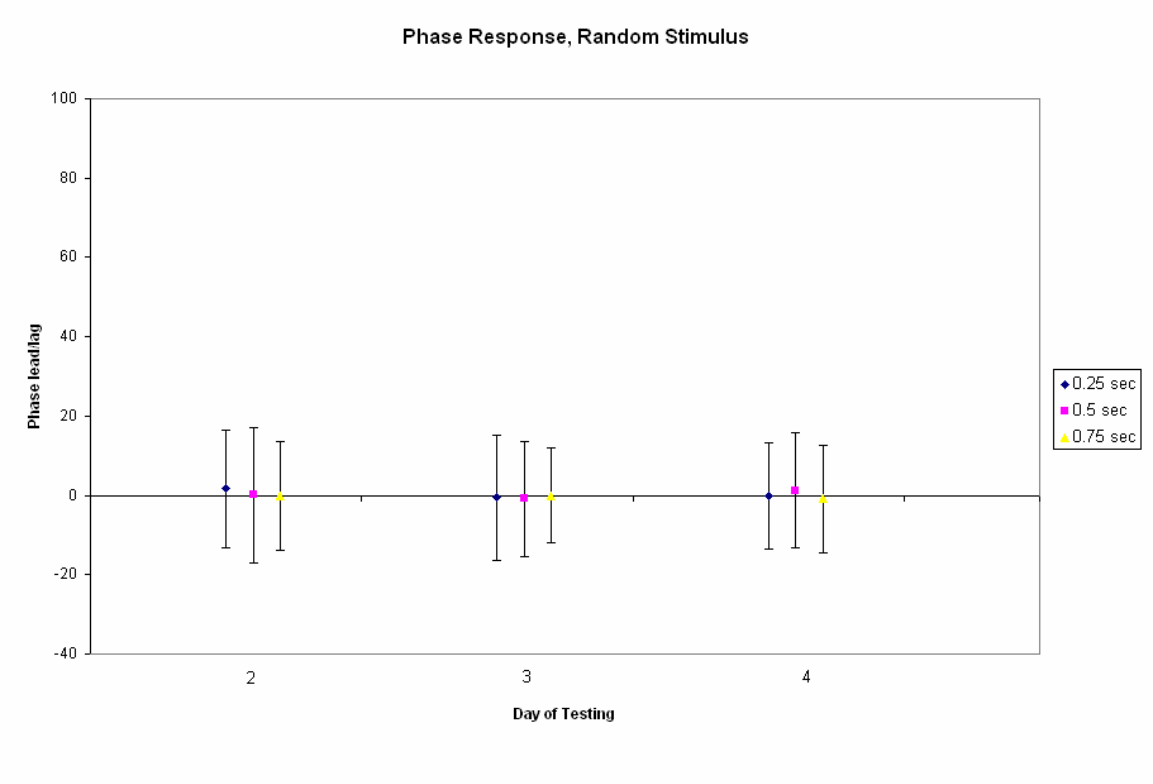

Figure 3.31 Phase Values, Random Stimulus

These values all were close to zero, regardless of the delay presented, which indicated subjects only being able to react to the stimulus on the screen, and not being able to predict. However, if a great number of crossings were missed, the data could be flawed.

Midline Crossing Matches, Random Stimulus

	Percentage of Crossings Matched			
		Random Stimulus		
Delay	**Day 01**	**Day 02**	**Day 03**	**Day 04**
0	46.52			
0.25		34.77	41.59	33.41
0.5		45.45	35.68	36.59
0.75		38.41	32.95	35.68

Table 3.22 Percentages of Midline Crossings Matched by Participants

DISCUSSION

Previous studies into the effectiveness of visual biofeedback in balance training have produced mixed results when evaluating the performance of patients during rehabilitation [20, 21, 22, 23]. A majority of the studies assume visual biofeedback to be a useful tool in retraining patients with vestibular and other problems that impair their balancing ability [21, 22]. This study has instead focused on if the visual biofeedback is rather a confounding variable. It is possible that patients are using the visual biofeedback as a predictive tool as they learn patterns of movement, rather than as a tool to provide them with feedback about their performances.

By introducing a delay between subject reaction and visualization of their reaction on the monitor in front of them, the study participants were forced to make a choice as to how they would respond to what they were seeing. In a test with no delay, the study participants were considered to be successful if they were able to move in such a way that matched up the response cross-hair with the target box. When a delay was introduced into the study, it created a situation where a subject correctly simulating the movement of the target box saw a crosshair that was lagging behind their movements on the monitor.

Therefore, with an introduced feedback delay, to match the target box with the response crosshair, the participants had to make predictive movements to compensate for the delay.

Error Graphs

In Figures 3.1 – 3.5, the averaged time-space response data was compared directly with the stimulus data to find error values through the testing. For Figures 3.1 and 3.2, error increased with the increased delay values, corresponding to 0.2 Hz and 0.4 Hz stimulus frequencies. In Figure 3.3, 0.6 Hz, the error values actually began to decrease for the highest delay value of 0.75 seconds compared to the previous error values. For a stimulus of 0.8 Hz, Figure 3.4 showed a decrease in error beginning with a delay of 0.5 seconds, and for the highest stimulus frequency, 1.0 Hz, error actually began decreasing from the delay of 0.25 seconds. All frequencies saw an increase in error from trials with no delay to trials with delays, and showed decreasing error as the trials progressed from beginning to end. The information from the error graphs seems to indicate increased difficulty tracking the target with delays imposed on the feedback system.

Responses to higher frequencies, based on the error trends, may have somehow benefitted from increased delays. It was possible that in higher frequency stimuli, the larger delays actually made the target movements appear closer to normal relative to the delayed subject icon. For example, in the case of a 1.0 Hz stimulus, a 0.75 second delay would actually appear to be a quarter of a cycle ahead of the movement, instead of three quarters of a second behind. As Table 4.1 points out, a phase delay of 0.75 seconds for a 1.0 Hz signal actual may have appeared as a 90 degree phase lead, as opposed to the 270 degree phase lag it was intended to be.

Random stimuli seemed to show no real change in error regardless of delay. The lack of change in error for the random stimulus supports the claim that the signal was unpredictable, and serves well as a control.

Gain Response

Gain response values, in the context of this experiment, corresponded with the study participants' ability to match the amplitude of the movement of the targets on the monitors in front of them. The target box was set to move through a region on the monitor proportional to the region of stability a subject could safely move through in a side-to-side sway. Gain values of 1.0 indicated that subjects were able to move their center of pressure (COP) in such a way as to track their target with movements of equal magnitude. Gain values of 0.5 corresponded to movements of 50% the magnitude, values of 0.7 corresponded to movements of 70% the magnitude, and so on.

With no delay introduced into the feedback system, gain response values, as indicated by Figure 3.7, showed tracking success for all periodic stimulus frequencies. The general shape of the gain distribution, with 0.6 Hz exhibiting a gain response of approximately 1.0, and gain values exhibiting a near symmetric decreasing distribution for higher and lower frequency values, can be considered typical for this type of setting.

However, Figure 3.8, gain responses when a 0.25 second delay was introduced into the feedback, shows a shift in the distribution, with symmetry around 0.4 Hz for the frequencies of 0.2 and 0.6 Hz, similar to Fig. 3.7, but with gain values for 0.8 and 1.0 Hz signals dropping to 0.3. The change in the distribution pointed to increased tracking difficulty for the higher frequencies with this delay value.

Figures 3.9 and 3.10, representative of delays of 0.5 and 0.75 seconds, respectively, continued this trend, with the distribution skewing further right, with tracking success only apparent for 0.2 Hz stimuli. These figures indicate attempts at tracking for 0.4 Hz, but with the 0.2 Hz stimulus showing the only real tracking success.

Again, the larger delays did show some improvement for the higher frequencies, in support of the possibility that higher frequencies and their corresponding phase degree values for the time delays may have affected their responses.

When further analyzing the gain responses in Figures 3.11- 3.14, gain tended to show a decrease with more days of testing, regardless of stimulus frequency and which delay value was introduced into the feedback system. Standard deviation values for the gain, variability, also showed a general pattern of decrease with more days of testing. These figures broke down gain responses by the day of testing and the delay value to look for trends. Although with a few exceptions, the trends for the gain responses tended to support the idea that subjects in the study improved their tracking ability with more experience.

The values in Table 3.9 support the findings in figures 3.7 through 3.10, again showing averaged gain values for various stimulus frequencies and the delays placed into the system.

Phase Response

Phase values, as seen in Figures 3.15- 3.20, showed in time-space the difference between the stimulus wave crossing the midline of the monitor and the participants' attempts to follow the motion of the stimulus. The horizontal axis was the number of the midline crossing event and the vertical axis was the difference in time between the crossing by the stimulus and the matched crossing by the participant. The figures are averaged for all participants for the same frequency, day, and delay. Figures 3.16- 3.20 looked at the phase responses for each frequency separately. For those figures, the first column, a 0.25 second delay, a perfect phase match would correspond to a value of 25.

For the second column, a 0.5 second delay, a perfect match would correspond to a value of 50. For the third column, a 0.75 second delay, a perfect match would correspond to a value of 75.

The amount of time a study participant was ahead or behind the stimulus waveform when it crossed the midline corresponded with the phase response values. For example, in the case of the 0.2 Hz signal, a study participant who predicted the position of the target and stayed exactly 5 seconds ahead of its movements would have been a full period ahead, which would have corresponded to a phase lead of 360 degrees. Similarly, if a person participating in the study was consistently behind the target box's movements by 5 seconds, their phase lag would have corresponded to phase values of -360 degrees. Table 4.1 shows what each time delay introduced corresponds to in terms of a phase lead or lag in degrees.

Delay	Frequency	0.2	0.4	0.6	0.8	1
	Period(T)	5	2.5	1.67	1.25	1
0.25	*Delay/T*	0.05	0.1	0.15	0.2	0.25
	Lag	18	36	54	72	90
	Lead	342	324	306	288	270
0.5	*Delay/T*	0.1	0.2	0.3	0.4	0.5
	Lag	36	72	108	144	180
	Lead	324	288	252	216	180
0.75	*Delay/T*	0.15	0.3	0.45	0.6	0.75
	Lag	54	108	162	216	270
	Lead	306	252	198	144	90

Table 4.1 Phase lag and lead values, in degrees, for perfect matching

Values showing phase leading suggested delay compensation and an ability to match response movements with the stimulus. Values showing phase lagging or values around zero suggested that either the subjects were unable to match the stimulus with their movements, or they simply ignored the feedback, and attended only to the stimulus.

For stimuli presented with no delay introduced, as in Figure 3.15, increased frequencies for the stimulus corresponded with more midline crossings to compare, and also decreased variability. In Figure 3.16, the phase responses for a 0.2 Hz stimulus were examined, with respect to both the delay presented and the day of testing. For the first day of testing, the phase responses were slightly negative, showing that study participants were behind in their timing for matching the midline crossings. For the first column, more days of testing show participants approaching the compensation level (25) more quickly. For the second day, the subjects overshot the compensation, showing they actually overcompensated for the delay, before settling close to it. For the 0.5 second delay, results for 0.2 Hz were very similar to the 0.25 second delay. With the 0.75 second delay introduced, results were similar, but participants were not able to reach the compensation level of 75.

Figure 3.17, 0.4 Hz stimulus, shows some attempts to compensate for the 0.25 second delay, but for higher delay values, the phase responses indicated an inability to lead the stimulus. 0.6, 0.8, and 1.0 Hz stimuli corresponded to Figures 3.18-3.20, and these phase responses indicated the same inability to lead the stimulus. As with no delay, there is a trend showing lower variability for higher frequency stimuli. The decrease in variability does not necessarily mean the participants were more successful at matching their movements more closely with the stimulus presented to them.

As with gain response, phase responses were evaluated separately by examining the day of testing and the delay introduced. When viewed this way, in Figures 3.21-3.24, a clearer trend is visible. Figure 3.21 shows the average phase response value for each frequency presented with no feedback delay. The value for 0.2 Hz represents a lag of 0.1

seconds, while the other values were effectively zero. Figures 3.22- 3.24 show the last three days of testing, with each of the different delays introduced into the feedback. In each figure, average phase values for each frequency and delay remained fairly consistent across days two through four.

However, when comparing different frequencies on each figure, it was clear that if slope lines were drawn across the various frequencies on each graph, the slope would become less negative with the increased delay values. The exception is for 0.2 Hz, which for 0.75 second delays had a significantly higher phase value than for all other frequencies. Again, this all pointed to a difference in the ability of participants to compensate for delays with the higher frequency values. For 0.2 Hz stimulus, the subjects were able to approach the compensation needed to account for the 0.25 and 0.5 second delays. For 0.2 Hz and 0.75 second delays, subjects were able to lead, but not able to fully compensate for the difference. 0.4 Hz stimuli elicited improvement in phase responses for the 0.25 second delay, but did not approach the correct compensation level. For higher delay values, 0.4 Hz stimuli were no better compensated for than 0.6, 0.8, or 1.0 Hz stimuli. Like before, this trend showed a decreased tracking ability with increased stimulus frequencies.

Matched Midline Crossings

To calculate the phase responses, it was necessary to compare all midline crossings within a plus/minus quarter-cycle of the stimulus wave. In the event that there were multiple response midline crossings in that area, the closest to the stimulus was chosen. In the event that there were no response midline crossings within the area around the stimulus wave, the corresponding stimulus midline crossing was not counted when

finding the average phase difference. Table 3.15 addressed how successful participants were at making body movements that crossed the midline of their center of pressure within a quarter-cycle of the stimulus' corresponding movement. In support of previous gain and phase responses, the 0.2 Hz stimulus's lowest percentage of matches was 88% and the 0.4 Hz stimulus's lowest percentage of matches was 72%. All other frequencies dropped into the 30-40% range on multiple trials. This meant that the lower variability among the higher frequency trials may have been due to poor tracking, or failed tracking, rather than an improvement in the group's responses. This also supported the gain and phase response findings that showed strong tracking ability for the 0.2 Hz stimulus.

Combined with a high percentage of matched crossings, gain values closer to one, and phase values that approached the compensation levels for the delays introduced, participants have been shown quantitatively to track a 0.2 Hz stimulus well. For the 0.4 Hz stimulus, participants were able to track, but nowhere near as well as the 0.2 Hz stimulus. For the higher frequency signals, study participants were not able to track the stimuli.

Random Stimuli

Since the random stimulus was actually a sum of three disharmonic sines, it was interesting to see the gain responses of each characteristic frequency. The three frequencies were 0.3 Hz, 0.8 Hz, and 1.6 Hz. While the gain response for 0.3 and 0.8 Hz were approximately zero for each delay and the no delay condition, participants did seem to at least attempt to track the highest frequency component. The gain value for the 1.6 Hz component with no introduced delay was 0.7 and indicated at least some success tracking the stimulus. With delays introduced, subjects produced gain values for the

highest frequency component between 0.3 and 0.4, which, again, showed some tracking, but very little. Figures 3.25 and 3.26 show the same information, but found slightly differently. Both show the gain responses just addressed.

In Figures 3.27-3.29, the random stimulus was examined for gain responses by delay and day of testing. Like with the gain evaluations before, there appeared to be some attempt at tracking for the highest frequency, 1.6 Hz, for the 0.25 second delay. For higher delay values, there seemed to be less difference between tracking ability for each of the characteristic frequency. This would seem to have indicated that with higher delays, study participants lost the ability to discriminate beneath the underlying frequencies.

When viewing the phase responses for subjects attempting to track the random stimulus, the characteristic frequencies were no longer important. Rather, phase response information was only concerned with matching corresponding midline crossings, like with the periodic stimuli. Figure 3.30 showed that for random stimuli, regardless of delay, there was no attempt to track or compensate for the imposed delays. The variability among the responses was low as well, similar to the higher frequency periodic signals. Figure 3.31 confirmed that subjects were not tracking the random stimulus, as was noted by all of the phase response averages being close to zero.

Similar to the periodic stimuli, the percentages of midline crossings that were matched were also examined. Table 3.23 highlighted that regardless of day of testing or delay in the feedback, the highest percentage matched was only 47%. The other values were all between 30 and 45%, again reinforcing that study participants were unable to effectively track the random stimuli.

Limitations

As with any experiment, there can be difficulties along the way. The main source of errors in this study came from interaction with participants. Although instructed simply to attempt to match their movements with the target box on the screen, a number of subjects became frustrated with the second day of testing and may have had several trials of little or no real movement. The gain and phase response data seemed to support this assessment. Others seemed able to grasp concepts quickly. In my opinion, the differences in responses to the study could be attributed to the background of the individual participants. Five of the eleven participants came from an engineering background, and most likely understood the project more than an average person might. In future studies, a larger and more representative sample of the general population would be a better experimental group.

Also, at the beginning of each trial, individual participants were asked to stand in the same position relative to the monitor and force plates. Markings were made on the floor and force plates for each study participant, so their individual region of stability could be repeated for each trial. Although asked to stand in their respective marked positions, it was impossible to say that they remained equidistant from the monitor for each trial.

Height was also a concern for correct assessment of reactions. Based on the height of the individual subjects and a stationary monitor, the visual biofeedback would be in a different place in an individual's normal field of vision. If some participants felt the need to look down or squat to comfortably view the visual biofeedback, it could have altered their normal ability to sway in response to stimuli.

Limitations with the study itself arose due to the resolution of the sampling rate, stimulus frequencies, and the delays chosen. Future studies would be served well to focus on frequencies between 0.2 Hz, where subjects seemed to track well, and 0.4 Hz, where subjects appeared to begin to have tracking difficulty. Also, with regard to the chosen frequencies, in future studies, I would recommend using disharmonic frequencies. It was possible that some of the limited successes of the higher frequencies were actually due to their movements being related to the 0.2 Hz wave (multiples). In terms of sampling resolution issues, a higher sampling rate would make no difference in the quality of the data gathered. Rather, sampling at too high of a rate might create artifacts due to background noise.

It would be beneficial to know at what frequency subjects lose the ability to track in a balance task. For that task, examining 0.20, 0.21, 0.22, 0.18, 0.19, etc. hertz frequencies (those surrounding 0.2 Hz) would give a better answer to that question. For delay values, to find at what value people lose the ability to compensate, values should be looked at around 0.25 seconds, and between 0.25 seconds and 0.5 seconds. Also, individual frequencies might be able to better compensate for the delay times if they were the time equivalent of specific phase angle differences, such as 45 or 90 degrees out of phase.

Also, trials longer than 20 seconds might allow study participants more time to adapt to patterns of movement in periodic stimuli.

Conclusion

The question posed in this research was, how does feedback delay influence the performance of a stimulus-response driven balance task? Using gain and phase responses for visual biofeedback systems used to aid in balance recovery tasks, it can be said that delays added into a feedback loop make the task of tracking more difficult. Feedback delay especially created difficulty for frequencies above 0.4 Hz, which showed poor gain and phase response values.

The first hypothesis posed earlier postulated that phase delayed visual feedback would cause decreased tracking gains, and that those gains would decrease further with increased stimulus frequencies. The gain response graphs in Figures 3.8 – 3.10 and 3.12 – 3.14 generally support this hypothesis. An anomaly of a slight increase in tracking gain for the stimulus frequency of 1.0 Hz can be partially explained with the theory that some combinations of stimulus and delay value could have actually created a phase lead situation of a smaller magnitude than the imposed lag. Table 4.1 illustrated that for higher frequency and delay combinations, this theory was plausible.

The second hypothesis proposed earlier suggested that predictive phase compensation would occur during the periodic tracking tasks regardless of the imposed response phase delay. The phase response graphs in Figures 3.15 – 3.20 clearly proved this hypothesis false. Although predictive phase compensation did occur regardless of the imposed delay for a stimulus frequency of 0.2 Hz, and some compensation was seen for a stimulus frequency of 0.4 Hz, higher frequencies showed no attempts at predictive phase compensation. In fact, both gain and phase values for the higher stimulus frequencies support the idea that the stimulus frequency at which subjects went from

being able to predict and compensate for phase delays falls somewhere between 0.2 Hz and 0.4 Hz.

The third hypothesis raised earlier claimed that predictive phase compensation would not occur during the non-periodic tracking tasks. This last hypothesis was clearly proven to be correct. In both gain and phase evaluations, it was clear that participants in the study were unable to track the target. Since the participants were unable to track the target, they were also unable to predict and compensate for the introduced phase delays.

In the context of the problem presented in this research, it should be clear that visual biofeedback systems and their effectiveness are affected by delay in the feedback loop. In clinical settings that use these visual feedback systems, if the computer running the feedback environment is outdated and/or damaged for any reason, it may run slower than would be required to gain satisfactory performance information. Therefore, it can be concluded that it is imperative that clinics utilizing balance training programs involving visual feedback use computers that allow the feedback system to relay information in as close to real-time as possible. With further research, it may be possible to discover the limit of human predictive compensation, but for now, it safe to say that the delay between subject movement and the feedback they see on the monitor in front of them needs to have the smallest delay possible to ensure accurate performance measurements.

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Appendix A: Matlab Code for gain and phase analysis

The Matlab code used for the gain and phase analysis followed the format below. For each set of calculations, a read-in file, and a calculations file were used for a specific stimulus frequency and delay value. For example, “read_in_02_00.m” and “calcs_02_00.m” were used for a stimulus frequency of 0.2 Hz, with a delay of 0 seconds. Other stimulus frequencies were 0.4 Hz, denoted as 04, 0.6 Hz, denoted at 06, 0.8 Hz, denoted by 08, and 1.0 Hz, denoted as 10. Delay values of 0.25 seconds, denoted as 25, 0.5 seconds, denoted as 50, and 0.75 seconds, denoted as 75, were also used in the experiment. The random stimulus was denoted as Ra. Any combination of stimulus frequency and delay value plugged into the file names “read_in_A_B.m” or “calcs_A_B.m,” where A is the denotation for the stimulus frequency, and B is the denotation for the delay value, will allow duplication of these results.

Read in data

```
%read_in_02_00.m

clear all;
time = dlmread('All_Days_Slim.txt','\t','a3..a2002');
freq = [0.2; 0.4; 0.6; 0.8; 1.0; 1.2];
days = [1 2 3 4];
index = [0:0.01:20.47];
filt = 151;

%Target values... usable for all delay values
%Left Target = Right Target
Target_02 = dlmread('All_Days_Slim.txt','\t','b3..b2002');
Transform_Target_02 = fft(Target_02,2048);
yT = Target_02;
Power_Target_02 = Transform_Target_02.*conj(Transform_Target_02)/2048;
Peak_Target_02 = max(Power_Target_02);
yT_ZCROSSINGS = zcross(yT);

%read in values based on day and delay
%Day 01
%No Delay
AC_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','d3..d2002');
AC_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','d20013..d22012');
AC_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','d30018..d32017');
AC_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','t2004..t4003');
AC_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','t20013..t22012');
AC_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','t28017..t30016');
```

```
AC_Day01_02_00 = [AC_Run01_Day01_02, AC_Run02_Day01_02,
AC_Run03_Day01_02, AC_Run04_Day01_02, AC_Run05_Day01_02,
AC_Run06_Day01_02];

AR_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','e3..e2002');
AR_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','e20013..e22012');
AR_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','e30018..e32017');
AR_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','u2004..u4003');
AR_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','u20013..u22012');
AR_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','u28017..u30016');

AR_Day01_02_00 = [AR_Run01_Day01_02, AR_Run02_Day01_02,
AR_Run03_Day01_02, AR_Run04_Day01_02, AR_Run05_Day01_02,
AR_Run06_Day01_02];

CB_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','f3..f2002');
CB_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','f20013..f22012');
CB_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','f30018..f32017');
CB_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','v2004..v4003');
CB_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','v20013..v22012');
CB_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','v28017..v30016');

CB_Day01_02_00 = [CB_Run01_Day01_02, CB_Run02_Day01_02,
CB_Run03_Day01_02, CB_Run04_Day01_02, CB_Run05_Day01_02,
CB_Run06_Day01_02];


DB_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','g3..g2002');
DB_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','g20013..g22012');
DB_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','g30018..g32017');
DB_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','w2004..w4003');
DB_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','w20013..w22012');
DB_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','w28017..w30016');

DB_Day01_02_00 = [DB_Run01_Day01_02, DB_Run02_Day01_02,
DB_Run03_Day01_02, DB_Run04_Day01_02, DB_Run05_Day01_02,
DB_Run06_Day01_02];

DL_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','h3..h2002');
DL_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','h20013..h22012');
DL_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','h30018..h32017');
DL_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','x2004..x4003');
DL_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','x20013..x22012');
DL_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','x28017..x30016');
```

```
DL_Day01_02_00 = [DL_Run01_Day01_02, DL_Run02_Day01_02,
DL_Run03_Day01_02, DL_Run04_Day01_02, DL_Run05_Day01_02,
DL_Run06_Day01_02];

EB_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','i3..i2002');
EB_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','i20013..i22012');
EB_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','i30018..i32017');
EB_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','y2004..y4003');
EB_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','y20013..y22012');
EB_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','y28017..y30016');

EB_Day01_02_00 = [EB_Run01_Day01_02, EB_Run02_Day01_02,
EB_Run03_Day01_02, EB_Run04_Day01_02, EB_Run05_Day01_02,
EB_Run06_Day01_02];

HO_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','j3..j2002');
HO_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','j20013..j22012');
HO_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','j30018..j32017');
HO_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','z2004..z4003');
HO_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','z20013..z22012');
HO_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','z28017..z30016');

HO_Day01_02_00 = [HO_Run01_Day01_02, HO_Run02_Day01_02,
HO_Run03_Day01_02, HO_Run04_Day01_02, HO_Run05_Day01_02,
HO_Run06_Day01_02];

JR_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','k3..k2002');
JR_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','k20013..k22012');
JR_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','k30018..k32017');
JR_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','aa2004..aa4003');
JR_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','aa20013..aa22012');
JR_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','aa28017..aa30016');

JR_Day01_02_00 = [JR_Run01_Day01_02, JR_Run02_Day01_02,
JR_Run03_Day01_02, JR_Run04_Day01_02, JR_Run05_Day01_02,
JR_Run06_Day01_02];

MM_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','l3..l2002');
MM_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','l20013..l22012');
MM_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','l30018..l32017');
MM_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','ab2004..ab4003');
MM_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','ab20013..ab22012');
MM_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','ab28017..ab30016');
```

```
MM_Day01_02_00 = [MM_Run01_Day01_02, MM_Run02_Day01_02,
MM_Run03_Day01_02, MM_Run04_Day01_02, MM_Run05_Day01_02,
MM_Run06_Day01_02];

PR_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','m3..m2002');
PR_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','m20013..m22012');
PR_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','m30018..m32017');
PR_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','ac2004..ac4003');
PR_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','ac20013..ac22012');
PR_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','ac28017..ac30016');

PR_Day01_02_00 = [PR_Run01_Day01_02, PR_Run02_Day01_02,
PR_Run03_Day01_02, PR_Run04_Day01_02, PR_Run05_Day01_02,
PR_Run06_Day01_02];

RR_Run01_Day01_02 = dlmread('All_Days_Slim.txt','\t','n3..n2002');
RR_Run02_Day01_02 = dlmread('All_Days_Slim.txt','\t','n20013..n22012');
RR_Run03_Day01_02 = dlmread('All_Days_Slim.txt','\t','n30018..n32017');
RR_Run04_Day01_02 = dlmread('All_Days_Slim.txt','\t','ad2004..ad4003');
RR_Run05_Day01_02 = dlmread('All_Days_Slim.txt','\t','ad20013..ad22012');
RR_Run06_Day01_02 = dlmread('All_Days_Slim.txt','\t','ad28017..ad30016');

RR_Day01_02_00 = [RR_Run01_Day01_02, RR_Run02_Day01_02,
RR_Run03_Day01_02, RR_Run04_Day01_02, RR_Run05_Day01_02,
RR_Run06_Day01_02];

Day01_02_00 = [AC_Day01_02_00, AR_Day01_02_00, CB_Day01_02_00,
DB_Day01_02_00, DL_Day01_02_00, EB_Day01_02_00, HO_Day01_02_00,
JR_Day01_02_00, MM_Day01_02_00, PR_Day01_02_00, RR_Day01_02_00];
```

Calculations

```
%calcs_02_00.m


clear Day01_02_00_SMOOTH;
clear Day01_02_00_ZCROSSINGS;
clear ZCrossings_Day01_02_00;
clear DiffZCrossings;

clear Gain_Day01_02_00;
clear Power_Day01_02_00;
clear Transform_Day01_02_00;
clear Peak_Day01_02_00;

clear Gain_Avg_Day01_02_00;
clear Gain_Std_Day01_02_00;
clear ZCrossings_Avg_Day01_02_00;
clear ZCrossings_Std_Day01_02_00;

num_stim_zcro = size(yT_ZCROSSINGS,2);
half_cycle = 2000/num_stim_zcro;
quarter_cycle = half_cycle/2;



for i = 1:size(Day01_02_00,2)
   Transform_Day01_02_00(:,i) = fft(Day01_02_00(:,i),2048);
   Power_Day01_02_00(:,i) =
Transform_Day01_02_00(:,i).*conj(Transform_Day01_02_00(:,i))/2048;
   Peak_Day01_02_00(:,i) = max(Power_Day01_02_00(:,i));
   Gain_Day01_02_00(:,i) = Peak_Day01_02_00(:,i)/Peak_Target_02;


   %Phase Calc
   %Smooth data
   y1 = yT;
   y2 = Day01_02_00(:,i);
   clear yf2;
   for j=1:length(y1)
      if j >= filt && j < length(y1)+1
         temp = 0;
         for k=j-filt+1:1:j
            temp = temp + y2(k);  %adds up values
         end
         temp = temp / filt;       %averages values
         yf2(j-(filt/2)+(0.5))= temp;    %store averaged value at midpoint
```

```
      end
   end

   Day01_02_00_SMOOTH(:,i) = yf2';

   temp_zcross = zcross(Day01_02_00_SMOOTH(:,i))';
   size(temp_zcross);

   % for this trial, go through the stimulus' crossings and
   % find the closest match for each crossing.
   for lcv=2:num_stim_zcro
      target_zcrossing = yT_ZCROSSINGS(lcv);

      % go through the stimulus' crossings and find the best match
      closest = -1;
      diff = 10000;
      rel_diff = 0;

      for lcv2=1:size(temp_zcross,1)
         if ( abs(target_zcrossing - temp_zcross(lcv2)) < diff)
            rel_diff = target_zcrossing - temp_zcross(lcv2);
            diff = abs(rel_diff);
            closest = temp_zcross(lcv2);
         end
      end

      if (closest < 0 || diff > quarter_cycle)
         % no value found for this stimulus crossing
         DiffZCrossings(lcv-1, i) = -1;
         ZCrossings_Day01_02_00(lcv-1, i) = 0;
      else
         % use the value found
         DiffZCrossings(lcv-1, i) = closest;
         ZCrossings_Day01_02_00(lcv-1, i) = rel_diff;
      end

   end

   Day01_02_00_ZCROSSINGS(:,i) = DiffZCrossings(:, i);
end

Gain_Avg_Day01_02_00 = mean(Gain_Day01_02_00');
Gain_Std_Day01_02_00 = std(Gain_Day01_02_00);
ZCrossings_Avg_Day01_02_00 = mean(ZCrossings_Day01_02_00,2);
ZCrossings_Std_Day01_02_00 = std(ZCrossings_Day01_02_00')';
```

```
% finds the number of crossings that were not found
crossings_not_found = sum(sum(DiffZCrossings == -1));

% Avg difference between response/stimulus with stddev error bars
errorbar(ZCrossings_Avg_Day01_02_00, ZCrossings_Std_Day01_02_00)
title('Average phase difference on Day 01, 0.2 Hz Stimulus, No Delay');
xlabel('Time');
ylabel('Phase Lead/Lag');
YLim([-100 100]);

% Avg the avg of the differences, and the avg of the stddevs
Avg_ZCrossings_Avg_Day01_02_00 = mean(ZCrossings_Avg_Day01_02_00);
Avg_ZCrossings_Std_Day01_02_00 = mean(ZCrossings_Std_Day01_02_00);

%write out relevant data
ZCrossings_Day01_02_00 = [ZCrossings_Avg_Day01_02_00,
ZCrossings_Std_Day01_02_00]

dlmwrite('ZCrossings_Day01_02_00.xls', ZCrossings_Day01_02_00, '\t');
G_Z_Day01_02_00 = [Gain_Avg_Day01_02_00, Gain_Std_Day01_02_00,0,0,0,
Avg_ZCrossings_Avg_Day01_02_00,
Avg_ZCrossings_Std_Day01_02_00,0,0,0,crossings_not_found];
dlmwrite('G_Z_Day01_02_00.xls', G_Z_Day01_02_00, '\t');
```

Appendix B: Matlab code for finding zero crossing

```
% ZCROSS  ( MatLinks) Find the zero crossings of an arbitrary function.
%
%   ZCROSS(X) finds the zero crossings in the given data vector X.
%
%   ZCROSS(X,W) ignores multiple (noisy) zero crossings occurring within
%   a moving window of length W.  The default value for W=1.
%
%   ZCROSS(...,'exact') linearly interpolates the data to yield the "exact"
%   zero crossings.  In this case the result will contain non-integer "indices"
%   into the data X which correspond to the interpolated zero crossing points.
%   Applying ROUND(ZCROSS(*)) will subsequently yield the integer-valued
%   indices of X closest to the actual zero crossings.
%
%   ZCROSS(...) plots X and marks the zero crossings.  I = ZCROSS(...) returns
%   the indices I closest to each zero crossing.  LENGTH(I) will thus equal the
%   total number of zero crossings.
%
%   [I,D]=ZCROSS(...) also returns the mean deviation from true zero at the
%   "zero" crossings.  If [I,D]=ZCROSS(...) is used with the 'exact' parameter,
%   D will yield the mean deviation from the interpolated zero crossing points.
%
%   When no zero crossings are found, I=0 is returned.
%
%   See also FINDPEAK.
%
%   Type HELP MATLINKS for a full listing of all MatLinks ToolChest functions.
%
function [I, D] = zcross(data, w, exact)
%=============================================================
%  Copyright  1998,2000 Julian Andrew de Marchi, Ph.D. (julian@matlinks.net)
%  Use & distribution covered by GNU General Public License (www.gnu.org)
%=============================================================
%------------------
% parse the inputs
%------------------
if (nargin==0), error('No data vector X supplied.');
elseif (nargin<2), w=1; exact=0;
elseif (nargin==2), exact=num2str(w);
  if (exact(1)>='0' & exact(1)<='9'), w=str2num(exact); exact=0;
  else w=1; exact=1; end;
elseif (exact~='exact')
  error('"exact" is the only valid interpolation.');
else exact=1;
```

```
end;
if (w~=fix(w) | w<=0),
  error('The window length W must be a positive integer.');
elseif (length(data)<w+1)
  error('Not enough data in X--zero crossing detection would be senseless.');
end;
%---------------------------
% locate the zero crossings
%---------------------------
ii=0;  II=1;  I(1) = 0;
for ix=2:length(data),
  if (sign(data(ix))~=sign(data(ix-1)) & sign(data(ix))~=0),
    if (ix-II>=w | II<w), ii=ii+1;
      if (exact), I(ii)=data(ix-1)/(data(ix-1)-data(ix))+ix-1;
      else II=ix-1; [dummy inx]=min(abs(data(II:ix))); I(ii)=II+inx-1; end;
    end;
  end;
end;
if (exact), D=zeros(1,ii);
  for ix=2:ii,
    II=abs((data(round(I(ix)))-data(round(I(ix-1))))*(I(ix)-floor(I(ix)))+data(round(I(ix-
1))))/(ii-1);
    D(ix-1)=D(ix-1)+II; D(ix)=D(ix)+II;
  end;
  D(1)=2*D(1); D(ii)=2*D(ii); D=D./2;
else
  P = mean(abs(data(I)));
end;
%-------------------------------------------------------
% plot the zero crossings if there's no output variable
%-------------------------------------------------------
if (nargout==0),
  hold off, plot(data), hold on, plot(1:length(data), data, 'c.');
  if (exact), plot(I, D(1:ii), 'mo'), title(['Interpolated zero crossings (w=' num2str(w) ')']);
  else plot(I, data(I), 'mo'), title(['Zero crossings (w=' num2str(w) ')']); end;
  if (exact),
    plot(1:length(data), ones(1,length(data))' * [max(D) min(D)], 'c:'), xlabel('i'),
ylabel('x(i)');
  end;
  zoom on;
end;
%=======================================================
% End-of-File
%=======================================================
```

Appendix C: Code for the creation of a queue

C Code, Queue.c

```
/*****
** Queue.c
** - implements the methods declared in Queue.h
** Notes
** - this package is provided as is with no warranty.
** - the author is not responsible for any damage caused
**   either directly or indirectly by using this package.
** - anybody is free to do whatever he/she wants with this
**   package as long as this header section is preserved.
** Created on 2004-01-20 by
** - Roger Zhang (rogerz@cs.dal.ca)
** Modifications
** -
** Last compiled under Linux with gcc-3
*/

#include <stdlib.h>
#include "Queue.h"

void queue_init(Queue *q)
{
    q->size = 0;
    q->head = q->tail = NULL;
}

int queue_size(Queue *q)
{
    return q->size;
}

void queue_push(Queue *q, void *element)
{
    if (!q->head) {
        q->head = (QueueNode*)malloc(sizeof(QueueNode));
        q->head->data = element;
        q->tail = q->head;
    } else {
        q->tail->link = (QueueNode*)malloc(sizeof(QueueNode));
        q->tail = q->tail->link;
        q->tail->data = element;
    }

    q->tail->link = NULL;
    q->size++;
}

void *queue_front(Queue *q)
```

```
{
    return q->size ? q->head->data : NULL;
}

void queue_pop(Queue *q, int release)
{
    if (q->size) {
        QueueNode *temp = q->head;
        if (--(q->size)) {
            q->head = q->head->link;
        } else {
            q->head = q->tail = NULL;
        }
        // release memory accordingly
        if (release) {
            free(temp->data);
        }
        free(temp);
    }
}

void queue_clear(Queue *q, int release)
{
    while (q->size) {
        QueueNode *temp = q->head;
        q->head = q->head->link;
        if (release) {
            free(temp->data);
        }
        free(temp);
        q->size--;
    }

    q->head = q->tail = NULL;
}
```

Header file, Queue.h

```
/*****
** Queue.h
** - defines a generic FIFO queue structure
** - maintains a void pointer in each node only
** - does not handle memory allocation for client data
** - supports optional memory deallocation for client data
** Notes
** - this package is provided as is with no warranty.
** - the author is not responsible for any damage caused
**   either directly or indirectly by using this package.
** - anybody is free to do whatever he/she wants with this
**   package as long as this header section is preserved.
** Created on 2004-01-20 by
** - Roger Zhang (rogerz@cs.dal.ca)
** Modifications
```

```
** -
** Last compiled under Linux with gcc-3
*/
#ifndef _RZ_C_QUEUE_
#define _RZ_C_QUEUE_

typedef struct _QueueNode {
    void *data;
    struct _QueueNode *link;
} QueueNode;

typedef struct _Queue {
    int size;
    QueueNode *head;
    QueueNode *tail;
} Queue;

/*****
** initialize an empty Queue
** must be called first after a new Queue is declared
*/ void queue_init(Queue *q);

/*****
** push a new element to the end of the Queue
** it's up to the client code to allocate and maintain memory of
"element"
*/ void queue_push(Queue *q, void *element);

/*****
** return the first element in the Queue, or NULL when the Queue is
empty
*/ void *queue_front(Queue *q);

/*****
** remove the first element (pointer) from the Queue
** set "release" to non-zero if memory deallocation is desired
*/ void queue_pop(Queue *q, int release);

/*****
** remove all elements (pointers) from the Queue
** set "release" to non-zero if memory deallocation is desired
*/ void queue_clear(Queue *q, int release);

/*****
** return current number of elements in the Queue, or 0 when Queue is
empty
*/ int queue_size(Queue *q);

#endif /* _RZ_C_QUEUE_ */
```

Vita

Craig Hoovler was born on February 22, 1982 in Raleigh, North Carolina. After graduating from Athens Drive Senior High School in Raleigh, NC in 2000, Craig attended the University of North Carolina at Chapel Hill. While at North Carolina, Craig worked with Dr. Charles Finley on cochlear implant technology and received dual bachelors degrees in Applied Science, with a Biomedical Engineering concentration, and Mathematics in 2004. Craig moved to Richmond, Virginia in August 2005 to pursue his graduate education at Virginia Commonwealth University. After completing his Master's degree, Craig will be attending law school beginning in the fall of 2008.