POSTURAL RESPONSES TO SUDDEN CHANGES IN SENSORY INPUT WHILE VIEWING OPTIC FLOW

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It has been established that information from the visual, somatosensory, and vestibular systems contributes to balance, but how this information is integrated remains unclear. Sensory integration is a temporally dynamic process in which the sources for sensory information are dynamically regulated and change as environmental conditions change. Significant differences in this dynamic regulation have been found among healthy young and old subjects, as well as subjects with vestibular disease.

The present research was designed to examine the impact of aging and unilateral vestibular disease on balance as subjects responded to rapid changes in visual and somatosensory input. The postural sway of 25 healthy young controls, 24 healthy older controls, and 7 older subjects with unilateral vestibular hypofunction (UVH) was measured while visual and proprioceptive transitions were induced. To produce a sudden change in the visual environment, the amplitude of a sinusoidally moving visual scene was rapidly increased. Somatosensory information was altered through the use of a support platform that rotated in proportion to body sway, thereby reducing information from the somatosensory system.

The power of anterior-posterior head velocity was calculated for the 20 s surrounding each transition. This segment was then broken into 5 s periods in order to investigate adaptation,

i.e. within-trial time-varying characteristics of postural sway. Habituation was studied by investigating the changes in postural sway over repeated trials. A mixed factor repeated measures ANOVA was conducted with the power of postural sway velocity (dB) as the dependent variable. The independent variables were trial repetition and the time period in relation to the stimulus transition. Subject type was the between-subjects factor.

Both healthy and vestibularly impaired older subjects were observed to sway more than healthy younger subjects during all experimental conditions. Following a decrease in reliable somatosensory input, all subjects showed an increase in postural sway power. This increase was greatest in older subjects with UVH. Though adaptation following the perturbation was seen in all subject groups, this process was slower in the patient group. Habituation was seen in most trial conditions, especially between the first and second presentations of a stimulus.

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1.0 SPECIFIC AIM

The purpose of this study was to examine how the combined effects of aging and unilateral vestibular disease influence postural control. With increasing age, humans tend to exhibit greater postural instability (Overstall, Exton-Smith et al. 1977; Dornan, Fernie et al. 1978; Wolfson, Whipple et al. 1992; Cohen, Heaton et al. 1996; Baloh, Corona et al. 1998a; Baloh, Jacobson et al. 1998c). There are many causes that are attributed to this decline in postural control. Of these, reduced sensory function and a defect or slowing of central integration processes may play important roles (Woollacott, Shumway-Cook et al. 1986; Ponds, Brouwer et al. 1988; Teasdale, Stelmach et al. 1991b). The result is that older adults may have more difficulty maintaining balance when confronted with either reduced or inconsistent information from their sensory systems, or a sudden change in postural demands (Dornan, Fernie et al. 1978; Teasdale, Stelmach et al. 1991b; Redfern and Furman 1994; Peterka and Benolken 1995; Cohen, Heaton et al. 1996; Hay, Bard et al. 1996; Baloh, Jacobson et al. 1998c; Borger, Whitney et al. 1999). People with vestibular disease also experience imbalance under these destabilizing conditions (Redfern and Furman 1994; Peterka and Benolken 1995; Baloh, Jacobson et al. 1998c).

Due to the large number of falls that occur among older adults every year, it is important to study the various conditions that can lead to destabilization and the resulting responses from older adults who may have a decline in one or more of their sensory systems. The present research was designed to examine the impact of aging and unilateral vestibular disease on balance as subjects respond to rapid changes in visual and somatosensory input. The Specific Aim of this project was:

Specific Aim: To explore the time-varying characteristics (such as habituation and adaptation) of postural sway in response to sudden transitions in either visual or proprioceptive conditions in older adults with and without unilateral vestibular hypofunction (UVH).

In the present study, we induced both visual and somatosensory transitions and studied their effect on young controls, older controls, and older people with UVH. To produce a sudden change in the visual environment, we increased the amplitude of a sinusoidally moving visual scene. To cause a change in the reliability of a subject's somatosensory information, we used a support platform that rotated in direct one-to-one proportion to anterior-posterior body sway ("sway-referencing" of the platform). We examined adaptation by studying the within-trial time-varying characteristics of the postural sway responses. We studied habituation by investigating the changes in postural sway over repeated trials. The hypotheses of this aim were as follows:

H.1) Following a perturbation to visual or somatosensory input, all subjects will show a change in postural sway power. During conditions when the visual amplitude increases or the platform changes from fixed to sway-referenced, sway power will increase. During the condition when the platform becomes fixed after being sway-referenced, sway power will decrease.

H.2) Following an increase in optic flow magnitude or a transition to a sway-referenced platform, the magnitude of the increase in sway power will be greater in older subjects than in young controls. Older subjects with unilateral vestibular hypofunction will have the greatest increase. Following the transition to a fixed platform, the decrease in sway power will be the least in the older subjects with unilateral vestibular hypofunction.

H.3) Following a change in visual or somatosensory input, adaptation (a decrease in sway over time), will take longer in older subjects. Older subjects with unilateral vestibular disease will experience a slower adaptation than healthy older subjects.

H.4) Habituation (a decrease in sway over like trials) will occur in all subjects groups. The effect is expected to be the least in those with UVH.

2.0 INTRODUCTION

2.1 CURRENT STATE OF KNOWLEDGE

2.1.1 Sensory systems involved in postural stance

The act of maintaining upright stance in humans is dependent on the integration of afferent information from the visual, vestibular, and somatosensory systems. Sensory information from these sources is not entirely redundant. Each system is specialized for sway detection and stabilization within certain frequency and amplitude domains. Visual stabilization of posture operates mainly in the low frequency range, at or below 0.1 Hz (Lestienne, Soechting et al. 1977). The contribution of the vestibular system is limited by the properties of its two components: the semicircular canals, which sense angular acceleration, and the otolith organs, which sense linear acceleration. The semicircular canals provide an accurate feedback signal for higher frequencies (above 0.1 Hz) while otolith afferents are more specialized to lower frequencies (0.5 Hz or below) (Nashner, Shupert et al. 1989). The working range of proprioception includes frequencies greater than 1 Hz (Diener and Dichgans 1988).

In addition to being specialized for certain frequency ranges, the sensory systems involved in postural stance become more or less important as environmental conditions change in everyday life. For instance, in the dark, people must rely primarily on the vestibular and proprioceptive systems for balance.

2.1.1.1 The influence of vision on postural sway Visual input is a crucial element in postural control. It is well documented that postural sway is greater when subjects stand with their eyes closed compared to when they have their eyes open (Dornan, Fernie et al. 1978; Black, Wall et al. 1983; van Asten, Gielen et al. 1988; Teasdale, Stelmach et al. 1991a; Redfern and Furman 1994; Turano, Rubin et al. 1994; Baloh, Jacobson et al. 1998b; Baloh, Jacobson et al. 1998c) and that postural sway in the dark is approximately twice as great as that in an illuminated environment (van Asten, Gielen et al. 1988; Redfern and Furman 1994).

Many studies have focused on moving visual environments and their effect on postural control (Bronstein 1986; Ring, Matthews et al. 1988; van Asten, Gielen et al. 1988; Redfern and Furman 1994; Peterka and Benolken 1995; Sundermier, Woollacott et al. 1996; Borger, Whitney et al. 1999; Loughlin and Redfern 2001; Loughlin, Redfern et al. 2003; Sparto, Jasko et al. 2004; Akizuki, Uno et al. 2005; Berencsi, Ishihara et al. 2005). This is a useful technique in studying the influence of vision on postural sway. It has been determined that postural sway increases when subjects are exposed to moving visual scenes (Ring, Matthews et al. 1988; van Asten, Gielen et al. 1988; Redfern and Furman 1994; Peterka and Benolken 1995; Sundermier, Woollacott et al. 1996; Borger, Whitney et al. 1999; Loughlin and Redfern 2001). This increase is greater in healthy older adults than in healthy younger adults, though it is not clear as to whether this finding is due to aging or age-related pathologies (Ring, Matthews et al. 1988; Sundermier, Woollacott et al. 1996; Borger, Whitney et al. 1999). It has also been found that the magnitude of sway in healthy young subjects saturates at high amplitudes of scene movement. This is not the case for healthy older adults or adults with vestibular disorders (Peterka and Benolken 1995; Borger, Whitney et al. 1999).

Several experiments have used a moving room protocol in which the subject stood on a force platform in a fixed inertial frame while a room moved around them. Sundermier and Woollacott et al. (1996) studied postural sway in response to visual flow through the use of a moving visual surround (6' x 8' wide and 8' long, enclosed on three sides and above) suspended from the ceiling. The unexpected incongruence of vision with somatosensation and vestibular information was found to be destabilizing in the older subjects, especially those with a history of falling. The authors concluded that sensitivity to optic flow increases as balance-related somatosensory function decreases (Sundermier, Woollacott et al. 1996).

A more common method in the past ten years has been to use computer generated optic flow either projected onto screens surrounding the subject or viewed directly on a computer screen (Redfern and Furman 1994; Loughlin, Redfern et al. 2003; Sparto, Jasko et al. 2004; Akizuki, Uno et al. 2005; Berencsi, Ishihara et al. 2005). Ring and Matthews et al. (1988) investigated the effect of age on postural control by exposing active, healthy subjects between the ages of 17 and 79 to computer generated optic flow. This was done by back-projecting a 16 mm film onto a screen in front of each subject. The film consisted of five 8 s sections, alternating between a blank screen and the linear movement of a pattern moving either towards or away from the subject ("visual push"). Ground reaction forces were recorded while the subject stood on a force platform, both with and without a foam pad located under the feet. The sway path in the anterior-posterior (AP) direction was found to increase logarithmically with increasing age (Ring, Matthews et al. 1988).

In order to learn more about the effect of visual environments on balance in the elderly, Borger and Whitney et al. (1999) compared postural sway responses of healthy elderly to healthy young subjects while viewing computer generated sinusoidal optic flow. Four moving scene amplitudes (2.5, 5, 7.5, and 10), two scene frequencies (0.1 and 0.25 Hz), and two platform conditions (fixed and sway-referenced) acted as the independent variables. The center of pressure (COP, the location of the vertical ground reaction force) was measured during quiet stance and during sixteen combinations of the above variables. The elderly subjects swayed more than the younger subjects under all optic flow conditions, especially when the platform was sway-referenced. The difference between the groups was greatest at high amplitudes of visual scene movement. These results indicated that the elderly are more influenced by visual motion than the young (Borger, Whitney et al. 1999).

Imbalance is also known to occur in response to rapidly changing visual environments, such as when elevator doors open and the rider's focal point changes instantly, requiring a recalibration of the body in space (Simoneau, Teasdale et al. 1999). Simoneau and Teasdale et al. (1999) studied postural responses to modifying the visual anchor. The opening of elevator-like doors forced a rapid switch from a stable nearby anchor to a farther away location. This sudden change in focal point caused COP displacements in both younger and older subjects. The older subjects had greater sway speed than the younger ones before the doors opened. They were also more affected by the opening of the doors, showing two to three times more COP range and speed than the younger subjects (Simoneau, Teasdale et al. 1999).

2.1.1.2 The influence of the vestibular system on postural sway The vestibular system is the sensory system that detects head position and head movement. The contribution of the vestibular system to postural control can be studied by examining balance in patients with vestibular disorders.

Lacour and Barthelemy et al. (1997) investigated the postural sway characteristics of fifty Meniere's disease patients both before and after unilateral vestibular neurotomy. Posturographic recordings were made on a fixed force plate when subjects had their eyes open (EO) or closed (EC). Sway was evaluated by calculating the percentage difference in sway area between the EO and EC conditions. Results were then compared to those of 26 age- and gender-matched control subjects. As expected, the patients before neurotomy had significantly greater sway than controls during both the EO (+52%) and the EC (+93%) conditions. After neurotomy, the postural sway levels in the patients were much higher during the first 2 weeks but over time matched preoperative values (Lacour, Barthelemy et al. 1997).

Peterka and Benolken (1995) investigated the influence of bilateral vestibular loss (BVL) on postural sway elicited by optic flow. Healthy subjects demonstrated a saturation of postural sway at large amplitudes of scene movement, whereas subjects with BVL did not. These results indicated that vestibular information is used to limit body sway.

As observed in Lacour and Barthelemy et al. (1997), people with vestibular deficits can typically regain their balance function over time as their visual and proprioceptive senses begin to compensate for their vestibular loss (Dornan, Fernie et al. 1978; Black, Shupert et al. 1989; Lacour, Barthelemy et al. 1997). This increased reliance on visual information is apparent in that they have been found to have appreciably greater postural sway while viewing optic flow compared to healthy individuals (Redfern and Furman 1994; Peterka and Benolken 1995; Loughlin, Redfern et al. 1996; Sundermier, Woollacott et al. 1996). Redfern and Furman (1994) studied this increased sensitivity to moving visual environments by comparing the postural sway of patients with vestibular disorders to healthy control subjects. Six visual conditions were presented monocularly with a 60 degree viewing field: (1) eyes closed, (2) eyes open with no optic flow, (3) sinusoidal expansions and contractions of a black and white radially checkered stimulus at 0.3 Hz, (4) sinusoidal expansions and contractions of a black and white checkered “tunnel” at 0.3 Hz, (5) a black and white checkered “tunnel” moving at constant velocity toward the subject, and (6) a black and white checkerboard moving vertically at a frequency of 0.3 Hz. The patients were found to have significantly more postural sway than the controls during all optic flow conditions. Both patients and controls displayed sway at the stimulus frequency, but this component was significantly greater in the patient group. This suggests that people with vestibular disorders are particularly affected by optic flow (Redfern and Furman 1994).

In addition to having higher levels of sway during optic flow, vestibular patients are also especially susceptible to visually induced vertiginous symptoms due to their greater reliance on visual information. Such symptoms have been found to occur most frequently when optic flow is rich or repetitive in nature, such as in grocery stores, crowds of people, and traffic (Bronstein 1995a; Bronstein 1995b).

2.1.1.3 The influence of somatosensation on postural sway Sensory information arising from mechanical, thermal, and chemical activation of the sensory receptors in skin, muscle, and viscera comprises somatosensation. Reliable somatosensory information (in particular, that coming from joint proprioception and cutaneous sensation) is known to increase postural stability.

The construction of altered support surfaces, either through the use of a foam pad on which the subject stands or a sway-referenced support platform, is a common way to study the contribution of somatosensory information to posture (Black, Wall et al. 1983; Black, Shupert et al. 1989; Teasdale, Stelmach et al. 1991a; Peterka and Benolken 1995; Cohen, Heaton et al. 1996; Baloh, Jacobson et al. 1998b; Baloh, Jacobson et al. 1998c; Borger, Whitney et al. 1999). Both methods maintain an almost constant ankle joint angle, which reduces the contribution of proprioceptive cues from muscle spindles in the ankle. Motion in the ankle joint is normally highly correlated with body sway. Thus, the use of an altered support surface is an effective way to create inaccurate somatosensory information.

Postural sway in the AP direction has been found to increase in old and young, as well as healthy and vestibularly impaired individuals when using either a sway-referenced surface or a foam pad (Black, Wall et al. 1983; Teasdale, Stelmach et al. 1991a; Peterka and Benolken 1995; Baloh, Jacobson et al. 1998b; Baloh, Jacobson et al. 1998c; Borger, Whitney et al. 1999). Teasdale and Stelmach et al. (1991a) conducted a study using a 5 cm thick foam surface to investigate the hypothesis that there is a slowing of cognitive-motor responses with advancing age. Reducing proprioceptive input created a condition which stressed slower, higher-level sensory integrative mechanisms of postural control rather than reflexive ones. A variety of postural sway characteristics were studied in both elderly and young adults with healthy vestibular systems under four conditions: eyes open and normal support surface, eyes open and foam support surface, eyes closed and normal support surface, and eyes closed and foam support surface. Results indicated that disrupting one sensory input was not enough to differentiate between the age groups due to compensation by the remaining sensory sources. Thus it is unlikely that the elderly have slower central integrative mechanisms. However, the elderly were significantly more affected by the alteration of both sensory inputs than the young. They concluded that the postural instability experienced by the elderly was the result of a defect, rather than a slowing, of integrative mechanisms (Teasdale, Stelmach et al. 1991a).

Baloh and Jacobson et al. (1998c) also studied the influence of somatosensation on balance through the use of a foam rubber pad (3 in. thick). The sway velocity of three subject types was analyzed: young healthy subjects, older subjects who reported normal balance, and older subjects who reported imbalance (either due to central or peripheral vestibular disorders or of unknown cause). Sway was recorded for 10 s periods while eyes were open or closed during four trial types: 1) stationary support surface, 2) stationary platform with foam rubber surface, 3) support surface tilting in the AP direction (0.01 Hz; 4 degrees peak amplitude), and 4) support surface tilting in the ML direction (0.01 Hz; 4 degrees peak amplitude). The older subjects were found to have significantly higher mean sway velocity in both the AP and ML directions than younger subjects for all trial conditions. The older subjects who reported imbalance had higher velocities of sway than their age-matched controls, especially during dynamic posturography (Baloh, Jacobson et al. 1998c).

A study by Peterka and Benolken (1995) found that the amplitude of AP postural sway could increase by a factor of 4 both in control subjects and subjects with bilateral vestibular loss when somatosensory cues were inaccurate. A sway-referenced posture platform was used to create inaccurate somatosensory orientation information, while a full-field visual surround was sinusoidally rotated at a variety of frequencies and amplitudes to evoke postural sway in the AP direction. The finding led to two important implications. First, subjects with vestibular loss do not utilize somatosensory cues to a greater extent than subjects with healthy vestibular systems. Second, the threshold for the use of vestibular information in controls is lower when somatosensory information is accurate (Peterka and Benolken 1995).

2.1.2 The effects of aging on postural sway

With increasing age, there is significant deterioration in the sensory systems that contribute to human balance (Manchester, Woollacott et al. 1989; Teasdale, Stelmach et al. 1991a; Wolfson, Whipple et al. 1992; Cohen, Heaton et al. 1996). For instance, there is a 40% reduction in hair cells within the semicircular canals and as much as a 20% reduction of hair cells in the otolith organs in people over the age of 70 (Rosenhall 1973). In the visual system there is a reduction in the number of axons in the optic nerve as well as a loss of low frequency visual spatial sensitivity (Sekuler, Hutman et al. 1980). Proprioception also declines with age due to weakened joint sensation and cutaneous vibratory sensation (Skinner, Barrack et al. 1984). Another common manifestation of aging is a decrease in sensory output from the lower extremities (Calne 1985). In addition to declines in the abilities of these systems, there is also a slowing of cognitive-motor responses, central integrative processes, and reflexive systems (Salthouse 1985; Woollacott, Shumway-Cook et al. 1986).

Understanding how the aging process affects these systems is important in studying the prevention of falls in the elderly. It is possible that as people age, sensory information becomes inaccurate, leading to greater difficulty in the processing and integration of this information. This could lead to an increased level of difficulty in coordinating the necessary postural responses to maintain upright stance.

It is possible that due to the above factors, older adults may have an especially difficult time adjusting to new sensory conditions when postural demands are abruptly altered. Several studies have focused on this idea. Teasdale and Stelmach et al. (1991b) studied the postural sway responses in older and younger adults submitted to successively reduced and augmented visual sensory conditions. When visual input was removed, both younger and older subjects responded with increased sway. However, when visual input was reinserted, younger subjects quickly adapted by reducing their sway while older adults showed an increase in sway followed by a lengthy return to baseline levels. They were thus unable to quickly utilize the added sensory information (Teasdale, Stelmach et al. 1991b).

Similarly, Hay and Bard et al. (1996) found that while both young and old subjects are greatly affected by the removal of reliable proprioceptive inputs (in the form of tendon vibration), only the elderly have difficulty maintaining balance when proprioceptive information is reinserted (upon turning the vibration off). While the young subjects were able to quickly incorporate the reinserted sensory input, some older adults took over 10 s to readjust (Hay, Bard et al. 1996).

In addition to having difficulty responding to changing sensory conditions, older adults may also experience difficulty responding to a potential loss of balance. A recent study by Ahmed and Ashton-Miller (2005) examined how age affects the ability of the central nervous system to determine that a loss of balance has occurred. They modeled the central nervous system as a mechanical system that must detect a failure in postural stability, called a control error anomaly (CEA). They found that older adults responded prematurely to CEAs. Their conclusion was that increased sensory or motor noise in addition to an elevated sensory threshold may result in a false CEA detection and an inappropriate response (Ahmed and Ashton-Miller 2005).

2.1.3 The time-dependent nature of postural sway

Sensory integration for the maintenance of upright stance is a dynamic process. Active feedback-controlled mechanisms contribute to corrective torque generation based on body motion detected by sensory systems. The source of sensory information used for this torque changes as the environmental conditions change (Peterka and Loughlin 2004). As a result, postural responses to perturbations change in time as well. Both adaptation (a decreased postural response to repeated perturbations within a trial) and habituation (a decreased postural response to repeated perturbations across trials) have been reported, as described below.

The ability to adjust postural control performance is very important both during normal activity as well as when a vestibular disorder is present. Additionally, the existence of habituation supports the use of rehabilitation exercises in people with disorders affecting postural control. Repeated exercises have been shown to improve postural control and generate functional and structural adaptation in the neuromuscular system in both middle-aged and elderly subjects (Hakkinen, Kallinen et al. 1996).

2.1.3.1 Adaptation The characteristics of postural sway have been found to change over short time intervals (on the order of ten seconds) (Carroll and Freedman 1993; Schumann, Redfern et al. 1995; Loughlin, Redfern et al. 1996; Perrin, Schneider et al. 1998; Loughlin and Redfern 2001; Loughlin, Redfern et al. 2003). Until the early 1990's, postural sway was assumed to be a stationary stochastic process. Carroll and Freedman (1993) were among the first to question the validity of this assumption by investigating the temporal properties of the mean and variance of postural sway of three healthy male subjects. The subjects were tested under three conditions: eyes open while standing on two feet, eyes closed while standing on two feet, and eyes open while standing on one foot. The COP on a force plate was then measured during multiple 60 s time periods. Transients were found in both the mean and the variance of postural sway, generally during the first 20 s of each trial. The authors concluded that postural control is a nonstationary process and new methods of analysis must be developed to incorporate these time-varying properties (Carroll and Freedman 1993).

Schumann and Redfern et al. (1995) first introduced and demonstrated the use of time-frequency analysis, a nonstationary spectral analysis technique that can characterize the time-varying nature of postural sway. Two experiments were conducted to demonstrate the utility of the technique. The first experiment was designed to create COP signals with known frequency characteristics. Five healthy subjects were instructed to sway about their ankles in response to a metronome as its frequency gradually changed from 2 Hz to 1 Hz over a period of 30 s. This task was done while standing on a force plate with eyes open looking straight ahead. In the second experiment, the quiet stance of ten subjects (five healthy and five with vestibular impairments) was measured while they stood on the force plate with their eyes closed for 100 s. This was done to study the low-frequency component of postural sway. Time-frequency distributions for the COP signal were created for each subject and trial. Visual inspection revealed nonstationary signals in both experiments (Schumann, Redfern et al. 1995).

Subsequent studies utilizing time-frequency analysis have provided insight that could not have been obtained with conventional techniques. Loughlin and Redfern et al. (1996) found that while healthy subjects appear to adapt to constant frequency visual perturbation, people with vestibular deficits do not (Loughlin, Redfern et al. 1996). In a later study by Loughlin and Redfern (2001), it was shown that similar spectral characteristics are seen in both young and old healthy subjects while viewing sinusoidal optic flow. Additionally, both groups showed an initial increase in sway at the stimulus frequency at the beginning of each trial that then declined over time (Loughlin and Redfern 2001).

Nonstationary spectral analysis techniques are especially useful in studying transient responses of the postural control system to changing stimuli. In the present study, changes in postural sway due to sudden transitions in the visual or proprioceptive stimuli are well-characterized by time-frequency analysis.

2.1.3.2 Habituation Habituation to repeated perturbations is a well-studied phenomenon. It has been observed in a variety of perturbation types, including galvanic vestibular stimulation (GVS), visual surround motion, and support-surface motion (Nashner 1976; Bronstein 1986;

Horak and Nashner 1986; Fransson, Tjernstrom et al. 2002; Balter, Stokroos et al. 2004; Mahboobin, Loughlin et al. 2005; Tjernstrom, Fransson et al. 2005). GVS is thought to alter the resting discharge of vestibular afferent neurons. Both habituation and adaptation have been observed in response to repeated or sustained stimulation, respectively. Balter and Stokroos et al. (2004) found both short-term and long-term habituation to repeated exposure to GVS. The aim of the study was to examine the response decline in GVS. Forty healthy subjects were subdivided into four equal groups, each completing 5 testing sessions with different between-test time intervals: 1 day, 2 days, 7 days, and 14 days. During the first testing session, short-term habituation was observed during the repeated exposures to GVS. Long-term habituation was only observed between the first and second testing sessions. The response amplitudes of the 2nd to 5th tests did not differ. The between-test time interval did not have an effect on habituation (Balter, Stokroos et al. 2004). A similar study by Tjernström and Fransson (2005) using posturography with vibratory proprioceptive stimulation also found between-test time interval to be insignificant (Tjernstrom, Fransson et al. 2005).

Bronstein (1986) studied habituation of visually evoked postural responses using a moving room paradigm as described in section 2.1.1.1. Nine subjects were exposed to discrete movements of a room, lasting approximately 12 s and approaching a maximum velocity of 2-3 cm/s. Some trials were performed with the subject standing on foam to reduce proprioceptive information. The typical postural response consisted of a primary component (displacement of the body in the direction of the stimulus) and a secondary component (corrective displacement in the opposite direction). Upon second presentation of the stimulus, the primary component of the postural response was absent, if proprioceptive information was accurate. When standing on foam, subjects had a larger primary component during the first presentation and showed little habituation during following trials. The author concluded that vestibulo-proprioceptive cues must take over the normally dominant role of vision when visual information is inappropriate. Though some studies have not observed habituation, Bronstein attributes this to differences in stimulus velocity and duration (Bronstein 1986).

A study by Nashner (1976) focused on the habituation of the long-latency ankle stretch reflex (also called functional stretch reflex, or FSR) during repeated unexpected exposures to platform rotations and translations. By using various combinations of rotations and translations, the FSR was made useful, of no use, or inappropriate. Five successive platform rotations in which the FSR was inappropriate followed a random number (between 5-20) of trials in which the FSR was useful. Following an unexpected change in the usefulness of the stretch reflex, the 5 subjects that were found to exhibit stretch reflex responses progressively decreased reflex gain during the ensuing 3-5 trials. The FSR always habituated to a level most appropriate for the stabilization of sway (Nashner 1976).

2.1.4 Sensory re-weighting

As described above, there are three main types of sensory information important to balance: vestibular, somatosensory, and visual. Under constant environmental conditions (such as stationary visual scene, eyes open, fixed support surface), it is generally accepted that the three sensory systems make fixed contributions to torque generation for upright stance to be maintained. However, several recent studies have concluded that under varying conditions, the relative contributions of the sensory systems change based on which sources can be interpreted as reliable (Maurer, Schweigart et al.; Bronstein 1986; Oie, Kiemel et al. 2002; Peterka 2002; Peterka and Loughlin 2004).

A negative feedback control model was developed by Peterka (2002) in which information from the senses was dynamically regulated based on changing environmental conditions. Sensory integration was investigated by evoking AP postural sway using pseudorandom rotation of the visual surround and/or support surface (amplitudes of 0.5, 1, 2, 4, and 8º) in both healthy adults (age range: 24-46 yrs) and adults with profound bilateral vestibular loss (age range: 45-58 yrs). A high contrast visual surround (half-cylinder shape with radius 70 cm) was tilted in the AP direction with the rotation axis collinear with the subject's ankle joints. Center-of-mass (COM) was recorded during six trial conditions that provided differing combinations of sensory information. During all trial conditions and rotation amplitudes, the subjects' responses were highly correlated with the stimulus motion. However, the stimulus-response data for controls showed an overall nonlinearity because the increase in sway amplitude lessened with increasing stimulus amplitude. Sensory re-weighting could account for this nonlinearity with subjects showing increasing reliance on vestibular cues with increasing stimulus amplitudes. Because the subjects with vestibular loss could not increase their dependence on their vestibular systems, they were unable to utilize a sensory re-weighting technique, and their responses remained linear (Peterka 2002).

Data that shows that a decrease in stability has been observed following the restoration of accurate sensory information is particularly compelling evidence for the theory (Teasdale, Stelmach et al. 1991b; Hay, Bard et al. 1996; Simoneau, Teasdale et al. 1999; Peterka and Loughlin 2004). One might predict using conventional ideas that environments providing access to accurate sensory information from all three sources would facilitate postural stability. The finding that the reinsertion of accurate information has been found to disrupt postural stability could be explained by the existence of a transient period following the addition in which an incorrect torque is generated based on the previous environmental conditions rather than the current ones (Peterka and Loughlin 2004).

To investigate this concept, Peterka and Loughlin (2004) studied the time-varying spectrum of postural sway velocity and then created two model simulations to further investigate their results. The postural sway of 12 healthy adults was analyzed while they stood on a support surface with their eyes closed. Each subject completed six trials, involving a combination of fixed, sway-referenced, and reverse sway-referenced (in which the support surface is tilted in opposite proportion to the subject's AP sway angle) conditions. In trials in which the support surface was sway-referenced and then returned to a fixed level, most participants displayed a temporary 1 Hz body sway oscillation that was significantly different from the typical oscillations seen during quiet stance. The 1 Hz oscillation was further enhanced when the platform transitioned from sway-referenced to reverse sway-referenced. In both conditions, too much corrective torque was generated in proportion to body sway. In other words, the sensory weighting was temporarily inappropriate for the new environmental conditions. The model simulations supported a dynamic re-weighting explanation (Peterka and Loughlin 2004).

Oie and Kiemel et al. (2002) investigated the simultaneous re-weighting of more than one sensory input in order to directly test the theory of sensory re-weighting. Ten young healthy subjects were presented with oscillatory somatosensory and visual stimuli (at 0.28 and 0.20 Hz frequencies, respectively) in which the amplitudes were varied individually. Gain was then calculated for each trial and stimulus. The observed nonlinear pattern provided further support for the hypothesis (Oie, Kiemel et al. 2002).

2.1.5 Summary of Background

Human postural control has been an active area of research over the past few decades. It has been established that information from the visual, somatosensory, and vestibular systems contributes to balance, but how this information is integrated remains unclear. It is known that sensory integration is a dynamic process and that changes in postural sway response occur both between trials (habituation) and within trials (adaptation). Additionally, significant differences have been found among healthy young and old subjects, as well as young and old subjects with vestibular disease. Though much progress has been made, there are still unanswered questions about these aspects of postural control. By studying how older adults with and without vestibular disorders respond to transitions in their sensory input, we hope to gain valuable insight into the postural control system.

2. 2 SIGNIFICANCE OF THE RESEARCH

Life expectancy in the United States has reached an all-time high (Hoyert 2005). As a result, the number of people over 65 is expected to more than double to almost 80 million between now and the year 2050. The population over age 85 is expected to grow at an even faster rate. In 1996, there were 3 million people in the Unites States over the age of 85. By 2050, the number is expected to be 19 million (Census 1995). Due to the growing number of elderly citizens, the issue of fall-induced injuries and deaths has become increasingly significant. In fact, unintentional injuries ranks fifth in the U.S. as a leading cause of death, and most of these deaths are related to falls (Kannus, Parkkari et al. 2005).

Vestibular disorders are frequently the source of postural instability in the elderly. Approximately 30% of elderly people with such disorders report falling (Whitney, Marchetti et al. 2004). In addition to increasing the risk of physical injury, vestibular disorders can also result in psychological stress and a lower quality of life due to the inability to perform certain daily activities (Honrubia, Bell et al. 1996). In order to address the issue of falls in the aging population, a great deal of research has focused on postural stability in the elderly. However, it is still not understood how the postural control system is affected by the combination of advanced age and vestibular disease. The aim of this research is thus to investigate postural sway of older adults both with and without vestibular disorders.

3.0 METHODS

3.1 OVERVIEW OF EXPERIMENTAL DESIGN

In order to investigate how older adults with and without unilateral vestibular disorders respond to rapid changes in either their visual or somatosensory input, an optic flow environment with a movable floor was used. This allowed us to systematically control the movements of both the visual scene as well as the support surface. The result was a quantitative assessment of how subjects respond to transient changes in their sensory environment.

3.2 SUBJECTS

Twenty five healthy young subjects (14 females and 11 males, mean age = 26.6, range of 21-37), 24 healthy older subjects (13 females and 11 males, mean age = 70.2, range of 60-80), and 7 older subjects with a unilateral vestibular disorder (5 females and 2 males, mean age = 66.7, range of 61-72) completed the study. A summary of the diagnoses and treatments for the older subjects with a unilateral vestibular disorder is given in Table 3.1. Informed consent was obtained from each subject before participation. The Informed Consent form was approved by the Institutional Review Board of the University of Pittsburgh.

All participants underwent an initial neurological screening exam before being scheduled for the experimental visits (although all subjects completed two days of testing, only data from the second day is presented here). In addition to an examination of cranial nerves, gross motor output, and cerebellar function, the assessment included tests of cognitive, visual, somatosensory, and vestibular function. The Mini-Mental State Examination (MMSE) was used to evaluate cognitive function (Folstein, Folstein et al. 1975). Subjects were excluded if they scored a 24 or lower. Two tests were used to detect impaired vision: a contrast sensitivity test and a visual acuity test. Subjects were required to have a corrected binocular visual acuity of at least 20/40 to participate. Somatosensation was assessed through the use of an ankle joint position sense test and a cutaneous pressure threshold test. Subjects needed to sense the vibration applied to their ankle as well as the 5.07 level of Semmes-Weinstein monofilament cutaneous pressure applied to the bottom of the foot.

To characterize the subject populations, vestibular function tests were performed to rule out or confirm the presence of a vestibular disorder. These included various electronystagmography (ENG) exams such as caloric testing and ocular-motor screenings, as well as an earth vertical-axis rotational test and a Sensory Organization Test (SOT).

Control subjects were excluded from the study if they had a history of otologic or neurologic disease, had a reduced vestibular response during caloric testing (greater than 24% loss), had a directional preponderance during rotational testing, or fell during two out of three trials of any one condition during the SOT.

A licensed physical therapist assessed the functional balance abilities of each subject using six well-known measures: the Dynamic Gait Index (Shumway-Cook and Woollacott 1995), the Functional Reach Test (Duncan, Weiner et al. 1990), the Timed Up and Go (Podsiadlo and Richardson 1991), the Short Physical Performance Battery (Guralnik, Simonsick et al. 1994; Guralnik, Ferrucci et al. 2000), the Falls History Screening, and the Survey of Activities And Fear Of Falling In The Elderly (Lachman, Howland et al. 1998). These tests were not used for exclusion.

Subjects classified as having unilateral vestibular hypofunction did not have any other neurologic conditions. A subject was considered to have UVH if caloric tests showed at least 50% reduced vestibular response in one ear only, or a 25-50% reduction in vestibular response in one ear only in addition to a directional preponderance on earth vertical-axis rotation testing. Subjects were excluded if their vestibular deficit was the result of a traumatic head injury.

Table 3.1 Summary of diagnoses and treatments for subjects with unilateral vestibular disease.

Subject	Age	Gender	Diagnosis	Treatment	Caloric Weakness
1	71	M	Unspecified peripheral disease	Non-surgical treatment	31% loss, right
2	67	F	Acoustic neuroma	Neurectomy	100% loss, right
3	66	F	Unspecified peripheral disease	Two gentamicin injections	100% loss, left
4	72	F	Acoustic neuroma	Gamma knife procedure	100% loss, left
5	66	M	Acoustic neuroma	Neurectomy	100% loss, left
6	64	F	Acoustic neuroma	Gamma knife procedure	100% loss, left
7	61	F	Acoustic neuroma	Gamma knife procedure	26% loss, right

3.3 EQUIPMENT

All testing took place at the Medical Virtual Reality Center, which is part of the Raymond E. Jordan Center for Balance Disorders. This center is part of the University of Pittsburgh's Department of Otolaryngology.

3.3.1 Optic Flow Environment

Subjects stood within a full field of view (FOV) display enclosure called the Balance NAVE Automatic Virtual Environment (BNAVE). The BNAVE is composed of three adjacent screens that surround the subject and fill 180 degrees of the horizontal and 70 degrees of the vertical FOV. The optic flow environment is created using custom software and displayed on three EPSON PowerLite 811p Multimedia Projectors, each of which back-projects onto one of three screens. A Dell Optiplex GX270D computer is connected to each projector. A fourth computer (Dell Optiplex GX 240) acts as a server that coordinates and synchronizes movement of the images across three screens.

Figure 3.2 shows a schematic of the visual scene that was used in this experiment. In the central FOV was a series of black and white concentric circles surrounding a central black circle 5º in radius. Each successive circle radius increased by 5º, creating a target pattern. The central circle was adjusted so that its center was aligned with each subject's eye height. The peripheral FOV was composed of a black and white checkerboard pattern. Each square was 15 cm x 15 cm.

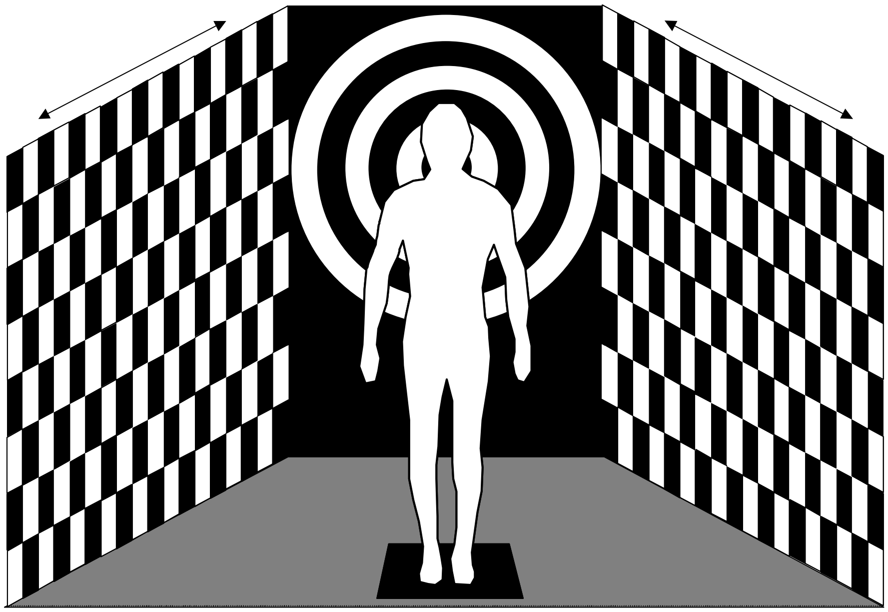

Figure 3.1 Schematic of subject in visual environment. Arrows indicate direction of sinusoidal optic flow. The concentric rings projected onto the central screen expanded and contracted radially. The checkerboard patterns on the left and right screens provided anterior-posterior laminar flow.

3.3.2 Posture Platform

Subjects stood on a NeuroTest™ (Neurocom, Inc.) posture platform, capable of moving with two degrees of freedom. During sway-referenced trials, the platform moved about an axis of rotation aligned with the each subject's medial and lateral malleoli. Direction and magnitude of rotation was proportional to the amount of sway in the pitch plane. The platform recorded ground reaction forces as well as its own rotational movements.

3.3.3 Tracking System

The postural sway of each subject was recorded using a Polhemus Fastrak™ electromagnetic tracking system. Two sensors were placed on the subject. A head sensor was attached to a plastic cap which was placed on the subject's head. A second sensor was located on a belt that was wrapped around the subject's waist at the level of the iliac crest. The sensors recorded head and pelvis sway in the AP, medial-lateral (ML), vertical, yaw, pitch, and roll directions.

3.3.4 Harness

To prevent injury from falls, a harness attached to an overhead support was used at all times during testing. It was designed to fit comfortably while not interfering with postural movements. The harness had been used in previous studies and had proven effective in accomplishing these goals. As an additional safety precaution, an experimenter stood behind the subject to provide physical support to stop an impending fall. A trial was stopped immediately and then repeated if a subject experienced a loss of balance.

3.4 PROCEDURE

Each subject was asked to remove his or her shoes before starting. An experimenter placed the harness and the two sensors on the subject. Before starting and after each of the trials, the subject was asked to rate their level of discomfort on a scale of zero to ten using the Subjective Units of Discomfort Scale (SUDS). A zero indicated no discomfort and a ten indicated a panic level of discomfort. Discomfort was defined to the subject as any feeling that was not normal to them, including dizziness, off balance, or anxiety. The scale was used to make sure the participant was not feeling any adverse effects during experimentation.

The blood pressure and heart rate of the subject were recorded before starting and between every 2-4 trials, when short rest breaks (2-3 minutes) were given to prevent fatigue. An experimenter aligned the subject's ankles with the rotational axis of the force platform. The experiment began with a 60 s baseline trial in which the subject was instructed to stand still on the force platform and look straight ahead onto a blank screen, keeping their eyes open and their arms crossed in front of them. During this period, the amount of sway that occurred naturally without perturbation (quiet stance) was measured.

This baseline trial was followed by 24 experimental trials, each lasting 50 s. Subjects were given the same instructions during the experimental trials with the exception that they were to focus on the central black circle in front of them. The trial conditions are summarized in Table 3.2. The shaded trials (conditions 1, 2, 5, and 6) were control trials, in which the environmental conditions did not change during the course of the trial. The unshaded trials (conditions 3, 4, 7, and 8) show the conditions of the 12 transitional trials, in which either the movement of the force platform or the visual scene amplitude changed at a random time between 20 and 30 s after the start of the trial. The order of the trials was fixed, so that every subject experienced the trials in the same order with identical trials occurring consecutively. Figure 3.2 shows a plot of the visual scene movement during a trial in which the amplitude was initially 4 cm and then increased to 12 cm at 25 s.

Table 3.2 Trial conditions. Shaded trials are control trials; unshaded trials are transitional trials.

		Platform movement		Scene amp. (cm)	
Condition	**Trials**	**Initial**	**Final**	**Initial**	**Final**
1	1-3	Fixed	Fixed	12	12
2	4-6	Fixed	Fixed	4	4
3	7-9	Fixed	Fixed	4	12
4	10-12	Fixed	Sway-referenced	4	4
5	13-15	Sway-referenced	Sway-referenced	12	12
6	16-18	Sway-referenced	Sway-referenced	4	4
7	19-21	Sway-referenced	Sway-referenced	4	12
8	22-24	Sway-referenced	Fixed	4	4

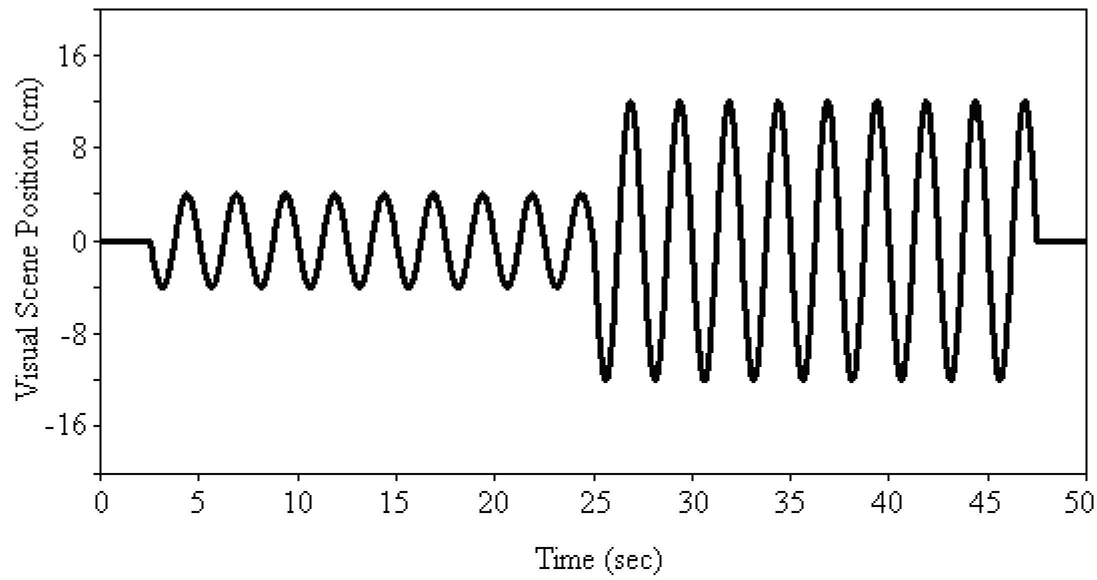

Figure 3.2 Visual scene movement during a trial in which the amplitude was initially 4 cm and then increased to 12 cm at 25 s. The frequency of scene movement was 0.4 Hz.

3.5 DATA COLLECTION AND ANALYSIS

Data from the Polhemus tracking system and the force plates were collected at a sampling rate of 20 Hz using LabVIEW (National Instruments). Data analysis was performed using MATLAB (The MathWorks, Inc.). As described in sections 3.3.2 and 3.3.3, we used a force platform that recorded COP as well as two sensors that detected movement of the subject's hip and head with 6 degrees of freedom. Because the visual scene moved in the AP direction, most postural sway also occurred in the AP direction. For this reason, analysis was restricted to AP head movement.

The head AP position signal for each 50 s trial was filtered with a 4th order lowpass digital Butterworth filter with cutoff frequency 2 Hz. The resulting signal was then differentiated to obtain the velocity of head movement.

The primary concern of the research was the effects of the visual and somatosensory changes that occurred within the transitional trials. Analysis was thus limited to the 20 s of data surrounding each transition. For the control trials, a 20 s period surrounding a random time in the middle of the trial was analyzed. Each 20 s segment was divided into four periods. For all conditions except condition 4, period 1 was the time from 10 s before the start of the transition to 5 s before, period 2 was the 5 s before the transition, period 3 was the 5 s after the transition, and period 4 was from 5 s after the transition to 10 s after the transition (Figure 3.3, top). In condition 4, the support transitioned from fixed to sway-referenced. Because it took approximately 3 s for the platform to become fully sway-referenced, periods 3 and 4 were shifted by 3 s, making the time from 3 s to 8 s period 3, and the time from 8 s to 13 s period 4 (Figure 3.3, bottom).

Figure 3.3 also shows examples of head AP position in relation to scene and platform movement. The top plot shows data from a trial in which the visual scene amplitude increased from 4 cm to 12 cm. The solid line is the movement of the visual scene, the dotted line is the head AP position, and the dashed line is the movement of the force platform (stationary in this trial). The bottom plot shows data from a trial in which the visual scene had a constant 4 cm amplitude and the force platform transitioned from fixed to sway-referenced. The y-axis is not to scale in either plot.

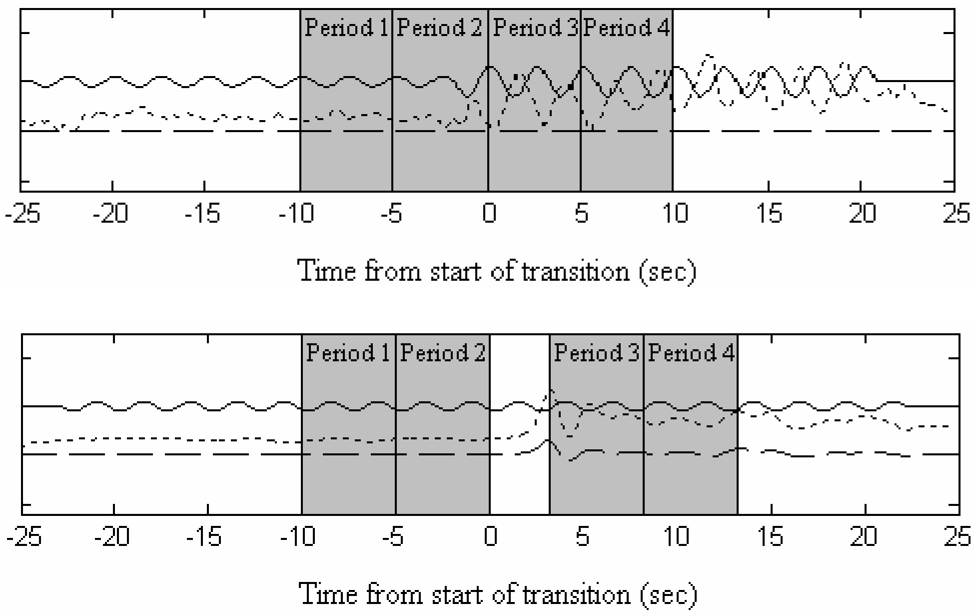

Figure 3.3 Time periods used for statistical analysis. Only the shaded portion of the trial was analyzed. The top plot shows the periods analyzed in all of the trials except 10-12 (condition 4). For the condition 4 trials, the periods shown in the bottom plot were used.

3.6 TIME-FREQUENCY ANALYSIS

Although analysis in the time domain is valuable in studying postural sway, it is based on the assumption that postural sway characteristics are time-invariant, i.e., the spectral characteristics do not change over the duration of the trial. However, biological signals, such as postural sway, are typically transient and nonstationary (Loughlin, Redfern et al. 2003; Shin, Gobert et al. 2005). Consequently, there is a need for a technique that allows analysis in both time and frequency. Time-frequency analysis, in which the time and frequency characteristics of the signal are studied simultaneously, is such a technique and has shown to be an important method of analyzing sway (Schumann, Redfern et al. 1995; Loughlin, Redfern et al. 1996; Loughlin, Redfern et al. 2003; Shin, Gobert et al. 2005).

Joint time-frequency densities (TFDs) are extremely useful in studying time-varying systems. The joint density function, $P(t,\omega)$, is the signal intensity per unit frequency and per unit time. The TFDs that were constructed in this research were positive TFDs, meaning they were always nonnegative and yielded the correct time and frequency marginals. These are the fundamental requirements of a proper TFD, i.e., nonnegativity and correct marginals. Together, they ensure that calculations made using the TFD are physically reasonable. If any part of the distribution is negative, quantities that are innately positive, such as the standard deviation in frequency at a given time, may have negative or imaginary values. If the marginals are incorrect, global quantities such as the duration and bandwidth of the signal will also be incorrect (Cohen 1989; Loughlin, Pitton et al. 1994; Loughlin, Redfern et al. 2003). The requirements also guarantee that the TFD is zero everywhere the signal or its spectrum are zero (Loughlin, Pitton et al. 1994).

Time and frequency marginals were obtained by integrating the TFD over frequency and time, respectively. Equations (1) and (2) represent the temporal density and spectral density of the signal s(t). The time marginal is also called the instantaneous power, while the frequency marginal can be referred to as the energy density spectrum.

$$\int P(t,\omega)d\omega = P(t) = \left|s(t)\right|^2 \tag{1}$$

$$\int P(t,\omega)dt = P(\omega) = \left|S(\omega)\right|^2 \tag{2}$$

The positive TFD was computed using a technique that combined the time-frequency information from multiple spectrograms. The spectrograms were found using the Matlab function *specgram*, which computes the windowed short-time Fourier transform of the signal. The spectrogram is the magnitude squared of this function. Mathematically, it is represented in equation (3), where x(τ) is the signal, h(t) is the window, and * denotes complex conjugation (Loughlin, Redfern et al. 2003).

$$P(t,\omega) = \left|\int x(\tau)h^*(\tau - t)e^{-j\omega t}d\tau\right|^2 \tag{3}$$

Multiple spectrograms were computed using different window lengths, and then combined to avoid the time-frequency resolution tradeoff inherent to spectrograms: the use of a wide window gives good frequency resolution but poor time resolution, while the use of a narrow window gives good time resolution but poor frequency resolution. By combining several spectrograms, a better estimate of the time-varying spectrum was achieved (Cohen 1989; Peterka and Loughlin 2004).

A variable obtained from time-frequency analysis is the average power present in a signal over a specific period of time. As mentioned above, time marginals are equivalent to instantaneous power. Therefore, to determine the average power, the time marginal was summed over the desired time range and then divided by the number of data points in the region. The equation for average power is given in equation (4), where N is the total number of data points in the chosen time period.

$$Power_{avg} = \frac{1}{N}\sum_{i=1}^{N} P_i(t) \tag{4}$$

The variable of interest in the present study was the average power of postural sway in the AP direction. The logarithm of this signal was calculated using equation (5) in order to stabilize the variance and normalize the distributions.

$$power(dB) = 10 * \log_{10}(power) \tag{5}$$

Fig. 3.4 is a sample TFD, normalized to signal energy, as well as the corresponding time and frequency marginals. The signal is the velocity of head AP sway from an older subject with UVH during one trial.

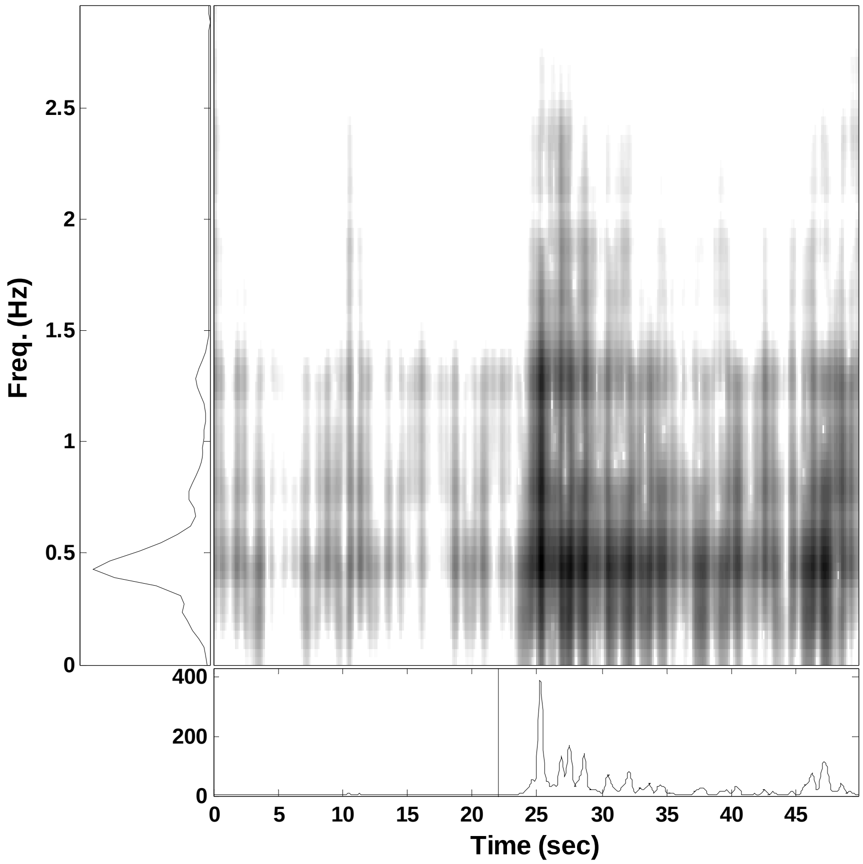

Figure 3.4 Positive time frequency distribution of the head AP sway velocity (dB) of an older subject with UVH. Darker areas show locations of highest signal energy. The trial included a platform transition from fixed to sway-referenced at 22 sec, as noted on the time marginal by the vertical line.

3.7 STATISTICAL ANALYSIS

Statistical analysis was used to quantitatively characterize the effects of aging and vestibular disease on balance. A mixed factor repeated measures analysis of variance (ANOVA) was conducted on each group of three identical trials. The dependent variable was the average power of postural sway velocity (dB). The independent variables were trial repetition (TRIAL: 1, 2, 3) and the time period in relation to the stimulus transition (PERIOD: 1, 2, 3, 4). Subject type (SUBTYPE: YC, OC, OV) was the between-subjects factor.

For each condition, ANOVAs were performed using a full model that included the main effects, two-way and three-way interactions. When a significant main effect was found, post-hoc analyses of pairwise comparisons were performed using Sidak's adjustment for multiple comparisons. A significance level of $\alpha = 0.05$ was used for each condition. For the transitional conditions (3, 4, 7, and 8), ANOVA of consecutive periods was done so that an evaluation of a) the stability of the pre-transition sway (periods 1 and 2), b) the effect of the transition (periods 2 and 3), and c) adaptation after the transition (periods 3 and 4) could be performed. Finally, the magnitude of sway power after the transition was compared with analogous control trial conditions.

The hypotheses will be addressed using the following analyses:

H.1) Following a perturbation to visual or somatosensory input, all subjects will show a change in postural sway power. During conditions when the visual amplitude increases or the platform changes from fixed to sway-referenced, sway power will increase. During the condition when the platform becomes fixed after being sway-referenced, sway power will decrease.

This hypothesis will be investigated by determining if there is a significant difference in the magnitude of sway power from period 2 to period 3.

H.2) Following an increase in optic flow magnitude or a transition to a sway-referenced platform, the magnitude of the increase in sway power will be greater in older subjects than in young controls. Older subjects with unilateral vestibular hypofunction will have the greatest increase. Following the transition to a fixed platform, the decrease in sway power will be the least in the older subjects with unilateral vestibular hypofunction.

This hypothesis will be tested by determining if there is a significant effect of subject type on the magnitude of the change in sway power from period 2 to 3.

H.3) Following a change in visual or somatosensory input, adaptation (a decrease in sway over time), will take longer in older subjects. Older subjects with unilateral vestibular disease will experience a slower adaptation than healthy older subjects.

This hypothesis will be examined by seeing if there is a significant decrease in sway power from period 3 to 4. Differences in adaptation between subject types will be determined.

H.4) Habituation (a decrease in sway over like trials) will occur in all subjects groups. The effect is expected to be the least in those with UVH.

This hypothesis will be investigated by examining the trial effect.

4.0 RESULTS

4.1 CONDITION 1: FIXED SUPPORT, 12 CM SCENE AMPLITUDE

The results from the first three trials of the experiment are shown in Figure 4.1, with statistical results in Table 4.1. These trials were control trials in which the visual scene amplitude was 12 cm and the support surface was fixed for the entire duration of the trial.

The average power of velocity was significantly affected by subject type ($p = 0.001$). Older controls (OC) had the greatest amount of sway power, followed by the older vestibular (OV) subjects and young controls (YC). Post hoc tests revealed a significant difference in sway power between young controls and older controls ($p = 0.001$) but not younger controls and adults with UVH or the two older subject groups. This is probably attributed to the large variance and small sample size in the OV group ($n = 7$).

Evidence of adaptation was observed, in particular during the first trial. Across subject type and trial repetition, a significant effect of period was found ($p < 0.001$). In trial repetitions 2 and 3, adaptation was more pronounced in OC than in OV and YC.

There was a clear decrease in sway velocity power during subsequent repetitions for all three subject groups, indicating evidence of habituation. Averaging across subjects, there was a main effect of trial ($p < 0.001$), with pair wise comparisons showing significant differences between all three trial repetitions. The largest reduction occurred between the first two trials. The amount of habituation depended on the subject type, as shown by the trial*subtype interaction ($p = 0.028$). The reduction in sway power was greatest in the older control group, who had a 4.47 dB decrease from trials 1 to 2 ($p < 0.001$) and a 1.78 dB decrease from trials 2 to 3 ($p = 0.022$). Although the power obtained from the OV group dropped from trials 1 to 3, no significant change was detected due to the limited sample size. Finally, the young control group showed the least amount of habituation, with a total decrease in power of 2.87 dB from trials 1 to 3 ($p = 0.003$).

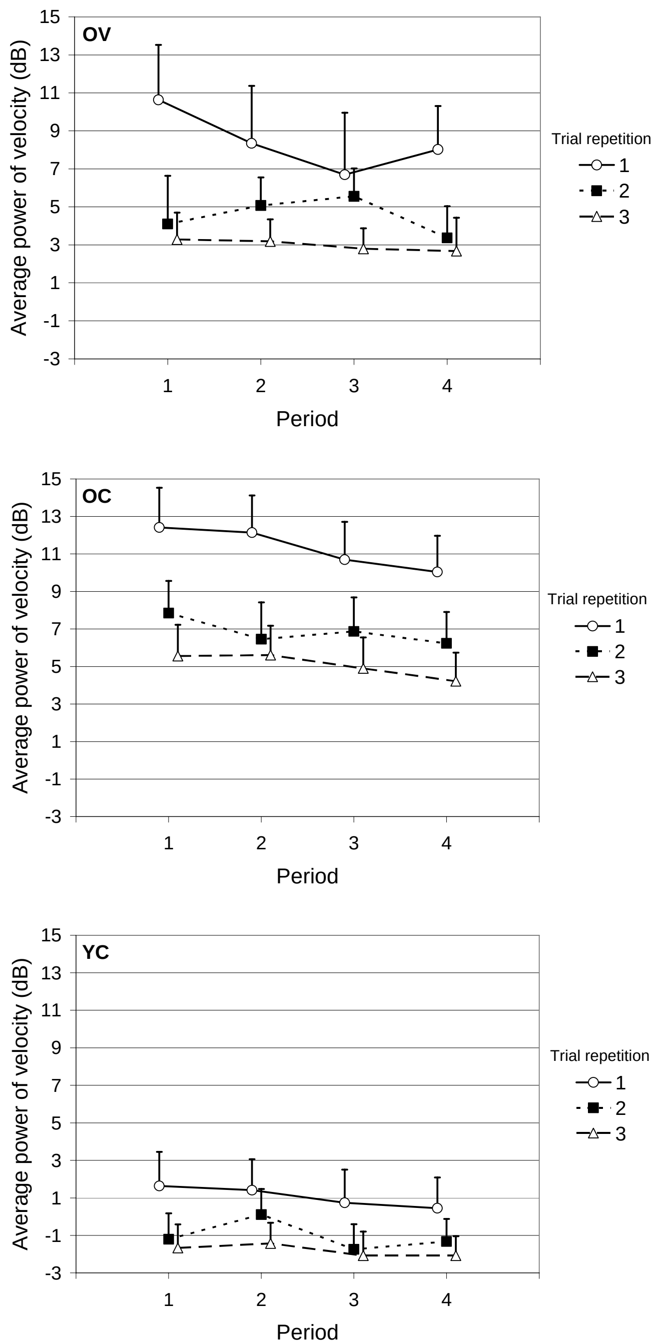

Figure 4.1 Average power of velocity (dB) during four 5 s periods of three control trials. During these trials, the visual scene amplitude was 12 cm and the support surface was fixed (condition 1). Results from each of the three subject groups are shown on separate plots, as noted in the subject type abbreviations in the upper left-hand corners. Error bars are the standard error of the mean.

Table 4.1 Summary of the ANOVA results for condition 1. Significant effects ($\alpha = 0.05$) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	p-value
trial	**< 0.001**
period	**< 0.001**
subtype	**0.001**
trial*subtype	**0.028**
period*subtype	0.390
trial*period	0.088
trial*period*subtype	0.137

Post hoc: trial repetition	p-value
1, 2	**< 0.001**
1, 3	**< 0.001**
2, 3	**0.020**

Post hoc: subtype	p-value
YC, OC	**0.001**
YC, OV	0.176
OC, OV	0.822

Post hoc: period	p-value
1, 2	0.987
1, 3	**0.019**
1, 4	**0.005**
2, 3	**0.016**
2, 4	**0.011**
3, 4	0.880

4.2 CONDITION 2: FIXED SUPPORT, 4 CM SCENE AMPLITUDE

Figure 4.2 shows the average power of sway velocity for each of the three subject groups during trials 4-6 (condition 2). These trials were similar to the first three trials with the exception that the amplitude of the visual scene was 4 cm.

Subject type was significant ($p = 0.004$), and the greatest sway power was elicited in OC, followed by OV and YC. As in trials 1-3, post hoc tests for trials 4-6 revealed a significant difference in sway power only between young controls and older controls ($p = 0.003$).

In this trial set, adaptation was not observed, as indicated by a lack of a period effect ($p = 0.722$). However, the main effect of trial was again found to be significant ($p < 0.001$), showing that habituation occurred in the second condition. Across subject groups, post hoc analysis showed a significant difference between the first trial repetition and repetitions 2 and 3 ($p < 0.001$). The overall reduction in power was 1.55 dB from repetitions 1 to 2 and 0.56 dB from 2 to 3. A summary of p-values is provided in Table 4.2.

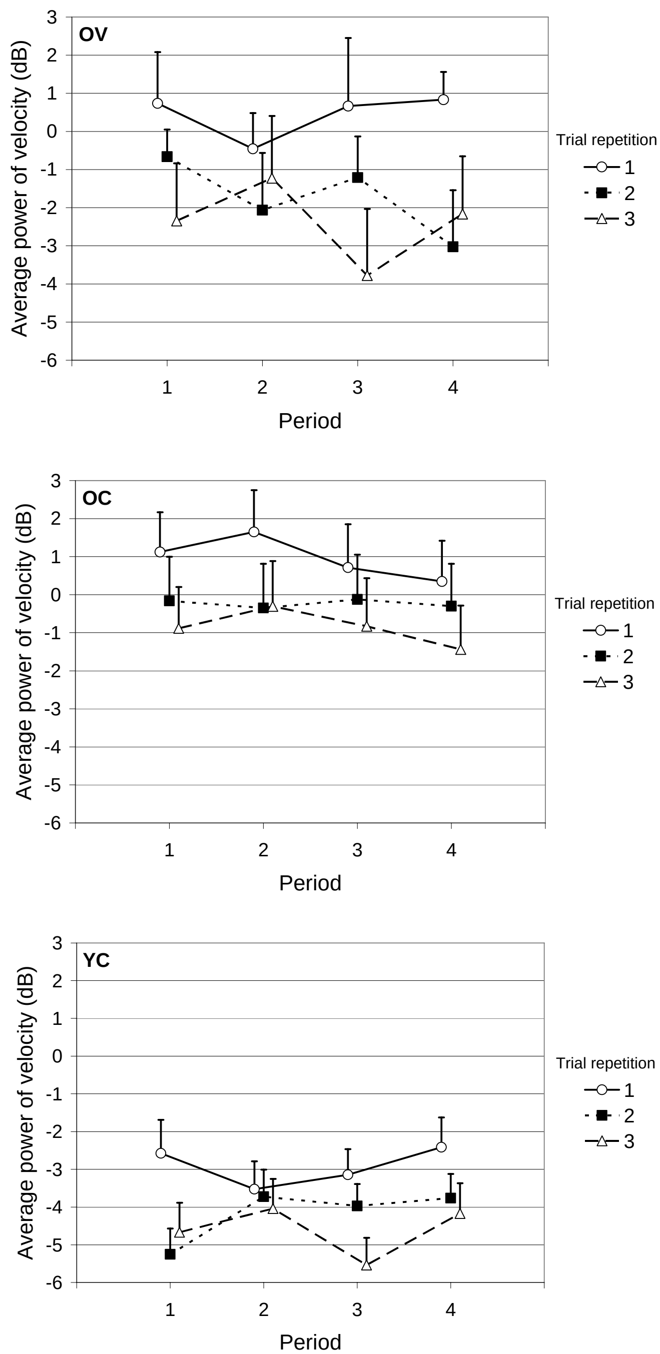

Figure 4.2 Average power of velocity (dB) during four 5 s periods of three control trials. During these trials, the visual scene amplitude was 4 cm and the support surface was fixed (condition 2). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.2 Summary of the ANOVA results for condition 2. Significant effects ($\alpha = 0.05$) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	p-value
trial	**< 0.001**
period	0.722
subtype	**0.004**
trial*subtype	0.811
period*subtype	0.362
trial*period	0.148
trial*period*subtype	0.203

Post hoc: trial repetition	p-value
1, 2	**< 0.001**
1, 3	**< 0.001**
2, 3	0.301

Post hoc: subtype	p-value
YC, OC	**0.003**
YC, OV	0.297
OC, OV	0.859

4.3 CONDITION 3: FIXED SUPPORT, 4 CM TO 12 CM SCENE AMPLITUDE

The first sensory transitions occurred in condition 3 of the protocol (experienced by the subjects during trials 7-9). The amplitude of the visual environment increased from 4 cm to 12 cm at a random time between 20 and 30 s into the trial (between periods 2 and 3). The force platform remained fixed for the entire 50 s.

Figure 4.3 shows the instantaneous power of sway velocity averaged over each subject group during the condition 3 trials. Data from the 30 s surrounding the transition (represented by a dotted line) are shown. In these ensemble time series, it appears that the power of sway velocity increases for the OV and OC subjects in trials 1 and 2. All other trials appear to be relatively flat.

Across all periods and trials, there was a significant subject type effect ($p = 0.002$, Table 4.3). The older control group had the greatest amount of sway, followed closely by the patient group and then the young control group. Post hoc tests showed significantly more sway among older controls compared to younger controls ($p = 0.001$). Across all subject types there was a main effect of period ($p < 0.001$), with an increase in power from periods 1 to 4. However, the magnitude of increase depended on subject type (period*subtype $p = 0.011$). There was an increase in power from periods 1 to 4 in OC (5.30 dB, $p < 0.001$) but not YC ($p = 0.157$). There appeared to be an increase in power in the OV group but the effect was not significant (3.65 dB, $p = 0.676$).

A significant trial effect was found ($p = 0.003$), such that power in trials 1 and 2 was greater than in trial 3 ($p < 0.015$). This effect was primarily mediated by an increase in power from periods 3 to 4 in trials 1 and 2 for the older controls and older patients (Figure 4.4).

For transitional trials such as those of condition 3, further analysis was done for each set of two consecutive periods so that three effects could be examined: the stability of the baseline (periods 1 to 2), the effect of the change in the sensory environment (periods 2 to 3), and adaptation after the transition (periods 3 to 4).

During the first two periods, the conditions remained constant and no period effect was found ($p = 0.466$). As expected, due to the amplitude change in the middle of each trial, sway increased from periods 2 to 3 ($p = 0.013$). As shown in Figure 4.4, the increase in sway power from period 2 to period 3 appeared mainly in the older subject groups.

In comparing the change in postural sway power from periods 2 to 3, the increase was marginally affected by subtype, as shown by the period*subtype interaction ($p = 0.051$). Pair wise comparisons showed that the older controls had a greater increase in sway power than the young controls ($p = 0.049$).

Between periods 3 and 4, the power of sway velocity continued to increase ($p < 0.001$), primarily in the older subject groups during the first two repetitions, while the power increased only slightly in the young control group. Overall, there was a main effect of subject type ($p = 0.001$), such that OC had significantly greater sway power than YC. There was also a main effect of trial ($p = 0.002$). Post hoc analysis revealed a significantly lower power of sway in the third repetition compared to the first and the second ($p = 0.002$ and $p = 0.040$, respectively). The interaction between trial and subject type was marginally significant ($p = 0.057$), and probably due to the increase in power seen with OC and OV in trial repetitions 1 and 2, in comparison with the minimal change found in YC.

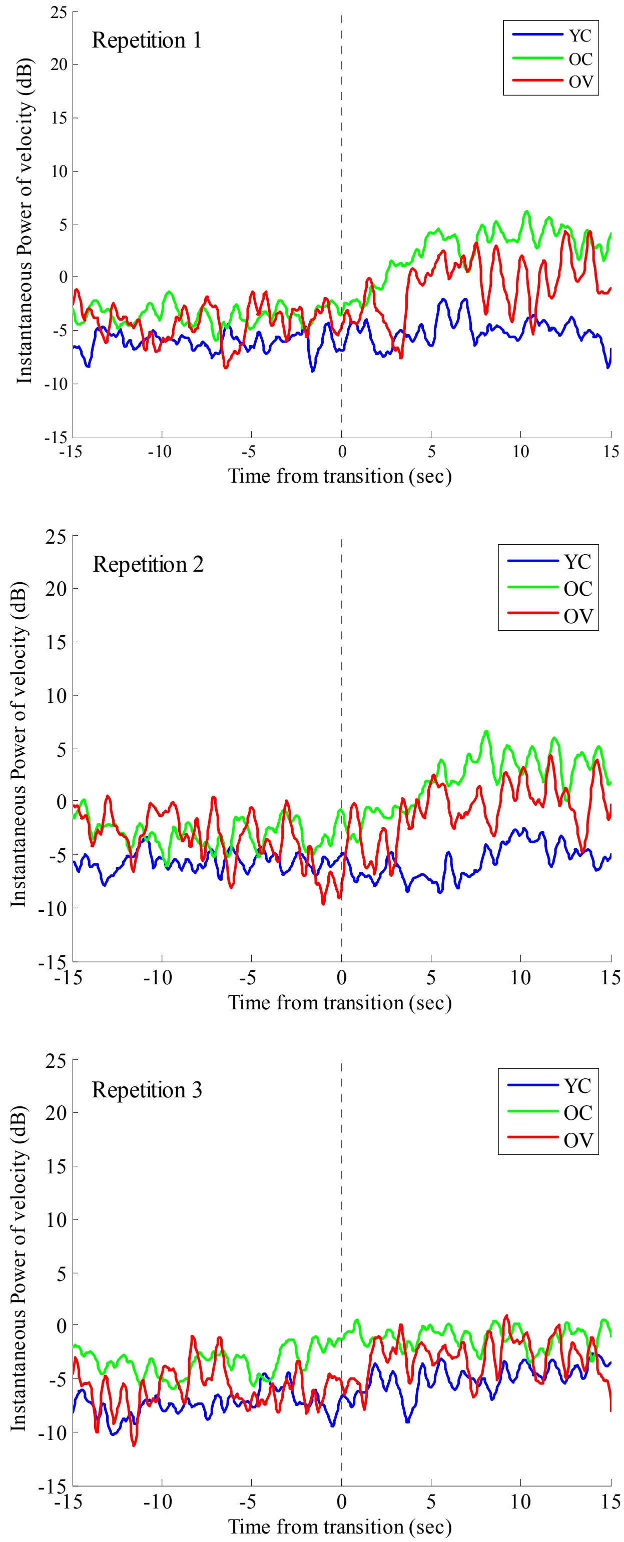

Figure 4.3 Instantaneous power of velocity averaged over each subject group. Trial repetitions are shown in separate plots, as indicated by the repetition number in the upper left-hand corner of each plot.

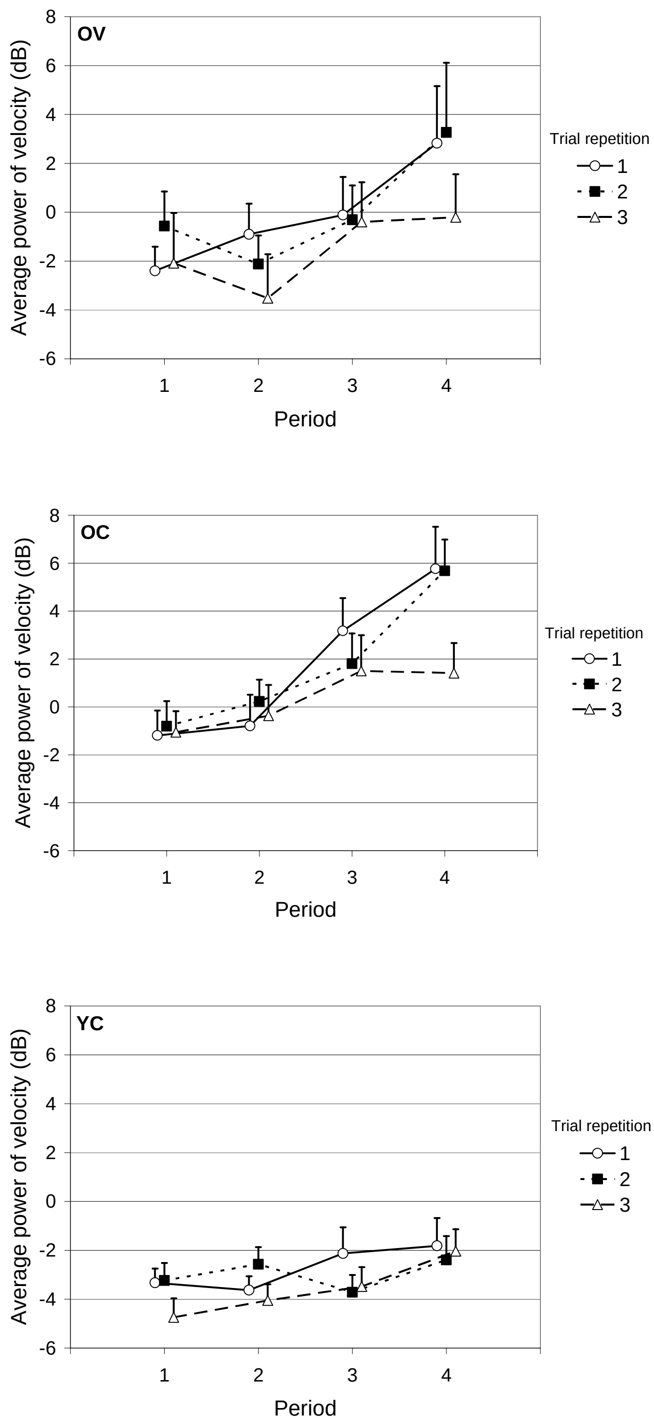

Figure 4.4 Average power of velocity (dB) during four 5 s periods of three transitional trials. During these trials, the visual scene amplitude increased from 4 to 12 cm between periods 2 and 3 while the support surface remained fixed (condition 3). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.3 Summary of the ANOVA results for condition 3. P-values with significant effects (α = 0.05) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
trial	**0.003**	0.110	0.210	**0.002**
period	**< 0.001**	0.466	**0.002**	**< 0.001**
subtype	**0.002**	**0.019**	**0.003**	**0.001**
trial*subtype	0.818	0.686	0.988	0.057
period*subtype	**0.011**	0.224	0.051	0.210
trial*period	0.093	0.759	0.231	**0.046**
trial*period*subtype	**0.030**	0.388	0.287	0.113

Post hoc: trial	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
1, 2	1.000	-	-	0.681
1, 3	**0.015**	-	-	**0.002**
2, 3	**0.012**	**-**	-	**0.040**

Post hoc: subtype	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
YC, OC	**0.001**	**0.016**	**0.002**	**0.001**
YC, OV	0.381	0.620	0.576	0.320
OC, OV	0.657	0.789	0.533	0.631

Post hoc: period	All periods
1, 2	0.977
1, 3	**0.002**
1, 4	**< 0.001**
2, 3	**0.013**
2, 4	**< 0.001**
3, 4	**< 0.001**

To investigate whether the increase in sway power observed after the increase in scene amplitude was due to the transition itself or merely the large scene amplitude, period 3 of condition 3 was compared to period 3 of condition 1 (Figure 4.5). During these periods, the support surface was fixed and the scene amplitude was 12 cm. A main effect of trial type (control vs. transitional) was present, with control trials showing an average of 4.23 dB more postural sway power than the corresponding transitional trials ($p < 0.001$). The effect was dependent on subtype (trial type*subtype $p = 0.025$), with YC showing a smaller difference in sway levels between trial types.

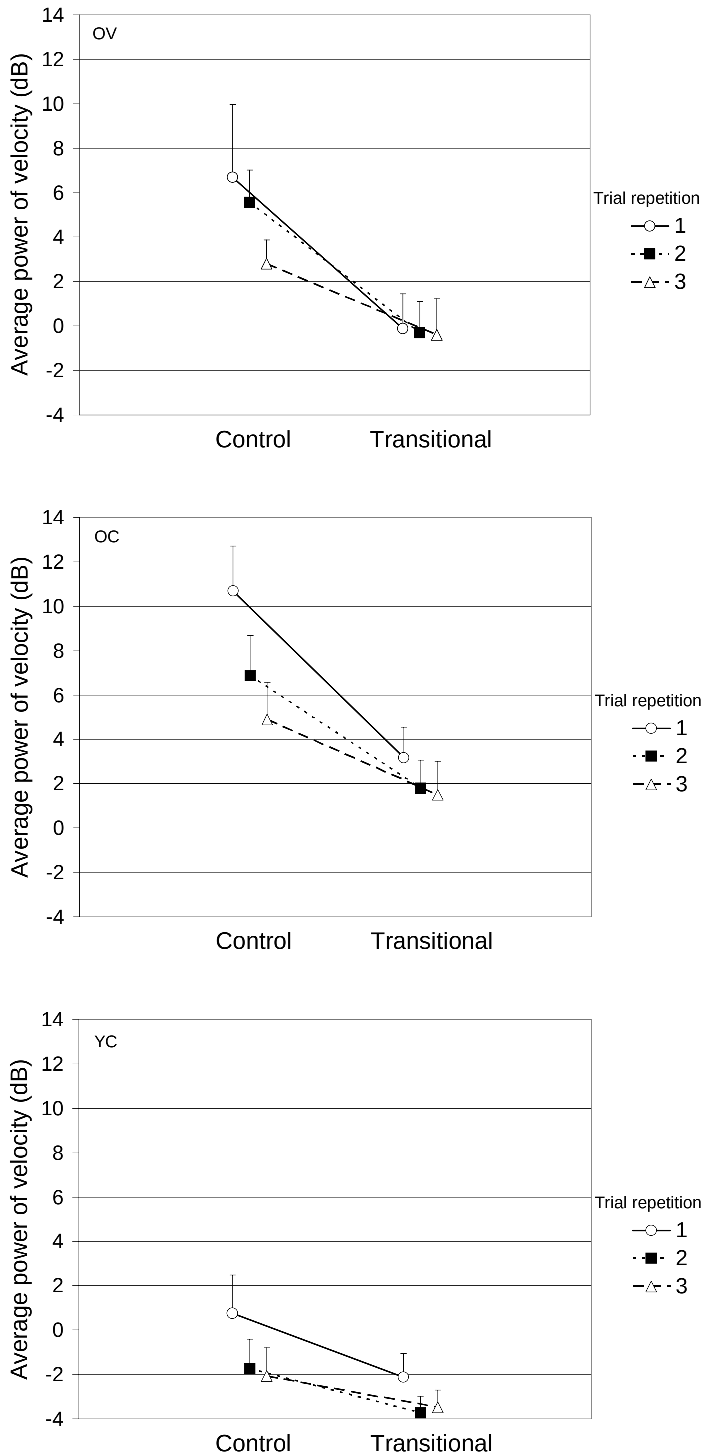

Figure 4.5 Average power of velocity (dB) during period 3 of conditions 1 (control) and 3 (transitional). During these periods, the support surface was fixed and the visual scene amplitude was 12 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Period 4 of condition 3 was compared to period 4 of condition 1 (Figure 4.6). During both of these periods, the support surface was fixed and the scene amplitude was 12 cm. The main effect of trial type was significant ($p < 0.001$). The power of sway during the transitional condition did not reach the overall level obtained during the control condition. An average of 2.13 dB more power was found in the control trials.

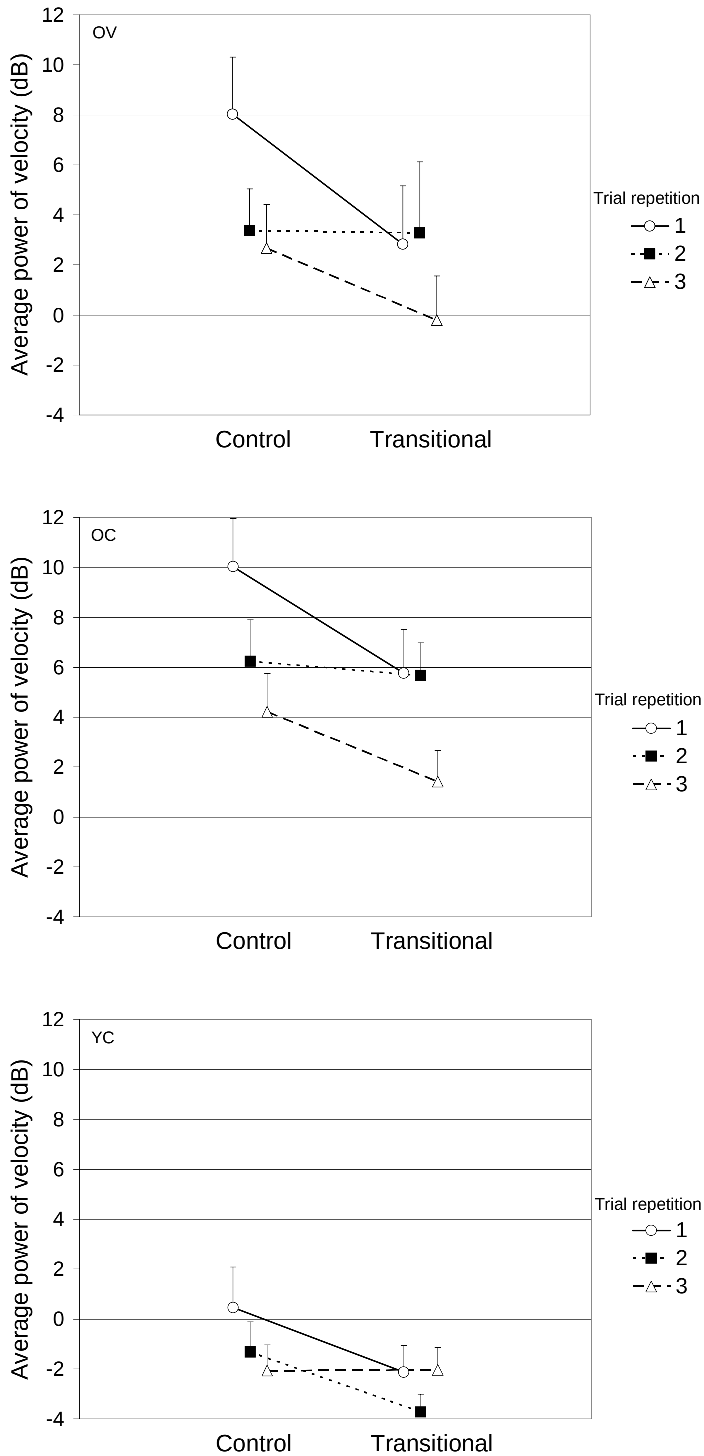

Figure 4.6 Average power of velocity (dB) during period 4 of conditions 1 (control) and 3 (transitional). During these periods, the support surface was fixed and the visual scene amplitude was 12 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

4.4 CONDITION 4: FIXED TO SWAY-REFERENCED SUPPORT, 4 CM SCENE AMPLITUDE

In condition 4, the support platform transitioned from a fixed state to a sway-referenced state mid-way through the trial while the visual scene amplitude was constant at 4 cm. Figure 4.7 shows the instantaneous power of sway velocity averaged over each subject group during the condition 4 trials. Data from the 30 s surrounding the transition (represented by a dotted line) are shown. The actual time course of the response to the perturbation and subsequent adaptation is best seen in this figure.

The average power of sway velocity (dB) is shown in Figure 4.8, with statistical results in Table 4.4. A main effect of subject type was present ($p < 0.001$). Across periods, the OC and OV groups had similar levels of sway power while the YC group had an average power of 3.87 dB less than the OV group ($p = 0.005$).

There was a clear effect of period ($p < 0.001$), with pair wise comparisons revealing significant differences between all pairs ($p < 0.001$) except periods 1 and 2 ($p = 0.999$). The effect of period was found to depend both on trial repetition (period*trial $p < 0.001$) and subject type (period*subtype $p = 0.050$).

The effect of trial was significant across subject groups and periods ($p = 0.003$). Post hoc analysis showed that the subjects had significantly less postural sway power during repetition 3 than repetitions 1 and 2 ($p = 0.001$ and $p = 0.042$, respectively). Habituation was clearly present in the younger control group (trial $p = 0.012$) and present to a smaller degree in the OC group ($p = 0.307$). Although habituation appeared to occur in the patient group as well, there was no trial effect, presumably due to a small sample size.

As in condition 3, further analysis was done to compare each set of two consecutive periods. Subject type was significant in periods 1 and 2 ($p = 0.001$), with young controls swaying significantly less than older controls (3.89 dB, $p = 0.001$). The older patients with vestibular disease swayed with 2.42 dB more power than the young controls, but the difference was not significant ($p = 0.282$). The level of sway power remained fairly constant for all subject types in periods 1 and 2 (period $p = 0.670$) within each trial. However, there was significantly less sway power in trial repetition 1 than in the following two ($p = 0.002$).

Additional analysis of periods 2 and 3 revealed a significant difference between subject types ($p < 0.001$) with younger controls showing less sway power than both OC and OV ($p < 0.001$ and $p = 0.002$, respectively). All three subject groups showed a clear disturbance resulting from the alteration of proprioceptive information as seen by the large increases in sway power between periods 2 and 3. There was a strong period effect ($p < 0.001$) across subject groups. The amount of increase depended on the trial, as indicated by interaction between trial and period ($p < 0.001$).

Figure 4.9 shows the increase in postural sway power between periods 2 and 3 for each subject group and trial repetition. In the first trial repetition, the overall disturbance experienced by the OV group was the greatest. It is interesting to note that the younger controls had a greater increase in sway power than the older controls. The magnitude of increase in power was smaller in trials 2 and 3. In trial 2, OV subjects continued to have a greater sway response compared with YC and OC. However, in trial 3, no clear difference was found between subject types. Overall, the amount of increase in trial 1 was 5.40 dB greater than in trial 2 ($p < 0.001$), which was 3.05 dB greater than in trial 3 ($p = 0.009$).

A comparison of periods 3 and 4 revealed the presence of post-transition adaptation in both the older controls (3.28 dB decrease, $p < 0.001$) and the younger controls (3.24 dB decrease, $p < 0.001$). Though the OV group had a decrease in sway power as well, the effect was not significant (3.20 dB, $p = 0.060$).

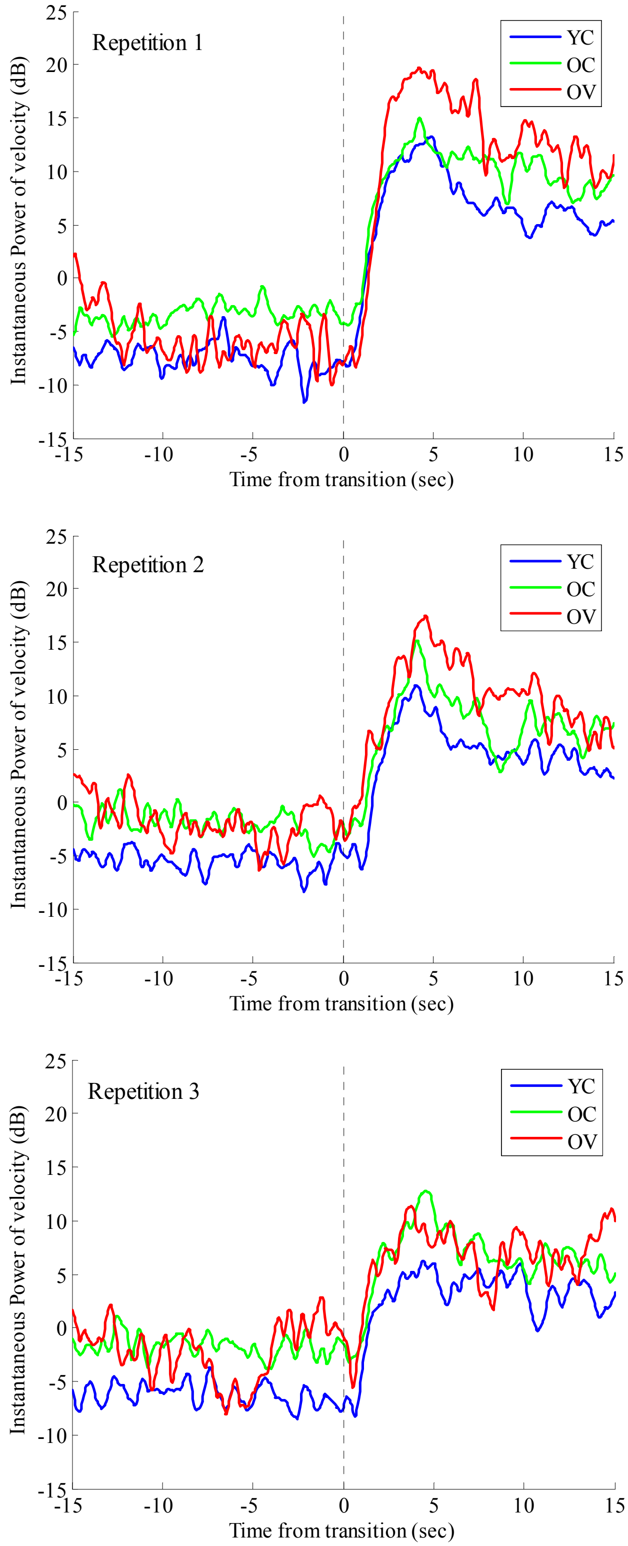

Figure 4.7 Instantaneous power of velocity averaged over each subject group. Trial repetitions are shown in separate plots, as indicated by the repetition number in the upper left-hand corner of each plot.

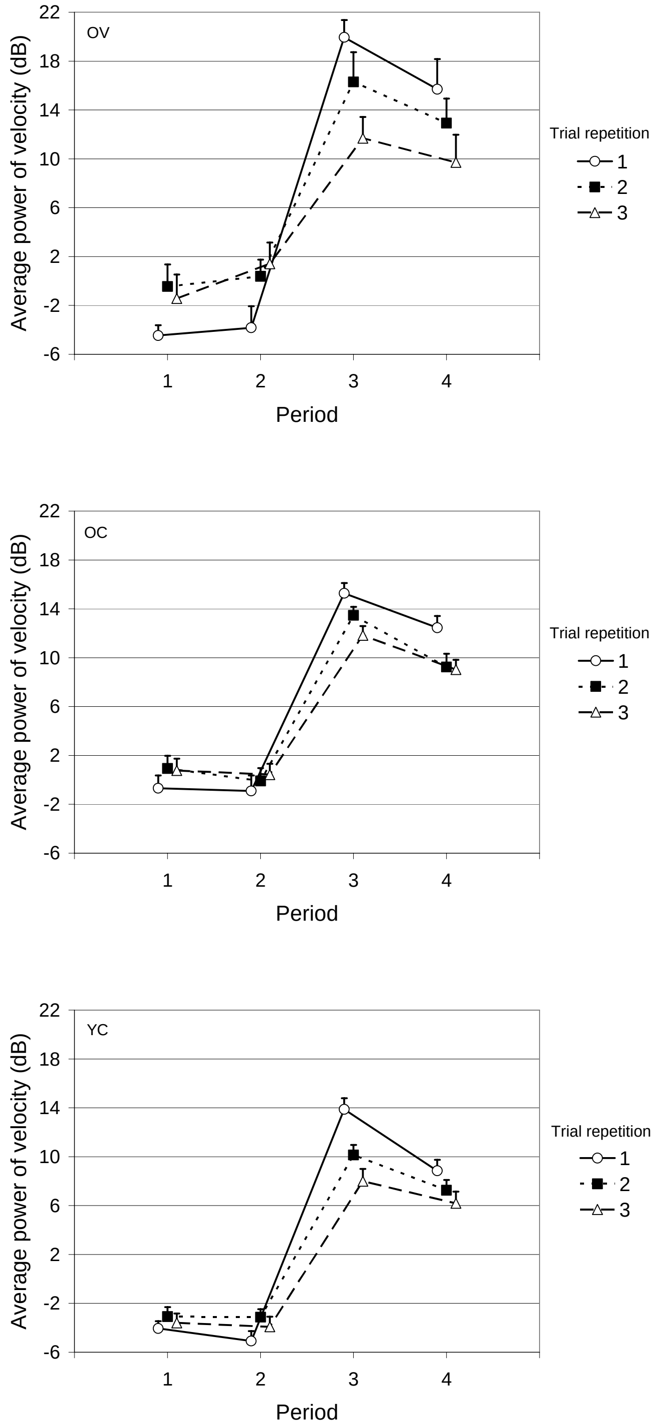

Figure 4.8 Average power of velocity (dB) during four 5 s periods of three transitional trials. During these trials, the visual scene amplitude was 4 cm. The support surface transitioned from fixed to sway-referenced between periods 2 and 3 (condition 4). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

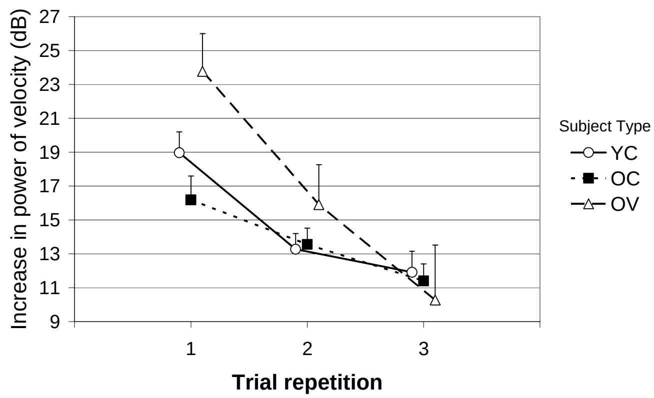

Figure 4.9 Increase in average power of velocity from periods 2 to 3 during condition 4 trials. Error bars show standard error of the mean.

Table 4.4 Summary of the ANOVA results for condition 4. P-values with significant effects (α = 0.05) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
trial	**0.003**	**< 0.001**	**0.005**	**< 0.001**
period	**< 0.001**	0.670	**< 0.001**	**< 0.001**
subtype	**< 0.001**	**0.001**	**< 0.001**	**< 0.001**
trial*subtype	0.589	0.256	0.602	0.232
period*subtype	**0.050**	0.108	0.234	0.997
trial*period	**< 0.001**	0.414	**< 0.001**	0.232
trial*period*subtype	0.167	0.577	0.076	0.389

Post hoc: trial	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
1, 2	0.902	**0.002**	0.864	**< 0.001**
1, 3	**0.001**	**0.002**	**0.012**	**< 0.001**
2, 3	**0.042**	0.992	**0.026**	**0.003**

Post hoc: subtype	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
YC, OC	**< 0.001**	**0.001**	**< 0.001**	**0.009**
YC, OV	**0.005**	0.282	**0.002**	**0.001**
OC, OV	0.963	0.689	0.796	0.203

Post hoc: period	All periods
1, 2	0.999
1, 3	**< 0.001**
1, 4	**< 0.001**
2, 3	**< 0.001**
2, 4	**< 0.001**
3, 4	**< 0.001**

Period 3 of condition 4 was compared to period 3 of its control equivalent (condition 6) to examine whether the increase in sway power observed after the alteration of proprioceptive information was due to the transition itself or merely the sway-referenced sensory condition (Figure 4.10). During these periods, the support surface was sway-referenced and the scene amplitude was 4 cm. An average of 5.00 dB more sway power was present in the transitional trials compared to the control trials ($p < 0.001$).

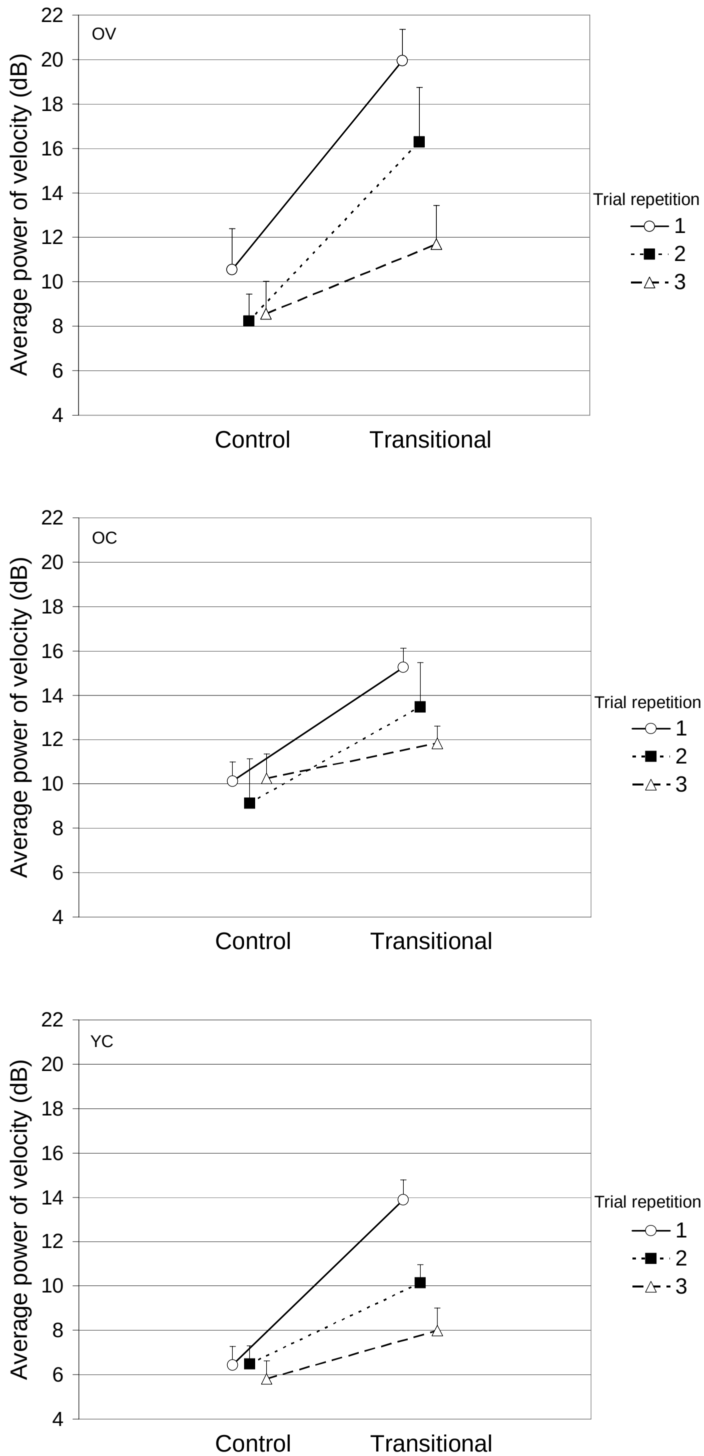

Figure 4.10 Average power of velocity (dB) during period 3 of conditions 6 (control) and 4 (transitional). During these periods, the support surface was sway-referenced and the visual scene amplitude was 4 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Post-transition (period 4) power levels in condition 4 were compared to baseline (period 4) levels in condition 6 in order to study the extent of the adaptation following the transition to a sway-referenced support surface (Figure 4.11). In both periods, the platform was sway-referenced and the visual scene moved with an amplitude of 4 cm. The main effect of trial type (control vs. transitional) was significant ($p = 0.001$) with average power in transitional trials exceeding that in control trials by 2.38 dB, indicating that by approximately 10 sec after the transition, sway had not returned to baseline levels.

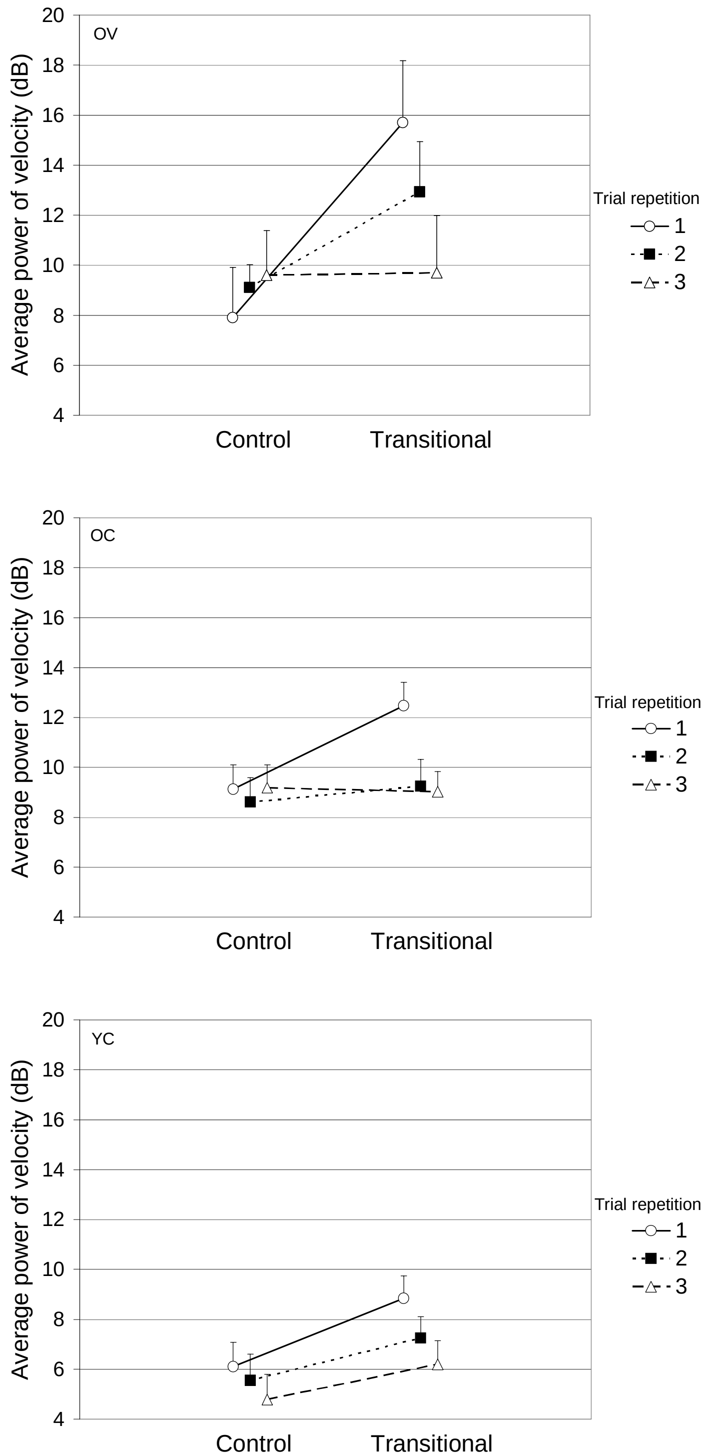

Figure 4.11 Average power of velocity (dB) during period 4 of conditions 6 (control) and 4 (transitional). During these periods, the support surface was sway-referenced and the visual scene amplitude was 4 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

4.5 CONDITION 5: SWAY-REFERENCED SUPPORT, 12 CM SCENE AMPLITUDE

Trials 13-15 (condition 5) acted as control trials, in which the support surface was sway-referenced and the visual scene amplitude was 12 cm for the entire trial. The main effect of subject type was found to be significant ($p < 0.001$). Figure 4.12 shows a clear difference in sway power between the young group and the older control group ($p < 0.001$) as well as the young group and the patient group ($p = 0.009$). The OC and OV groups had almost equal levels postural sway (OC greater than OV by 0.06 dB). The younger controls had considerably less sway (5.33 dB less than the OV group).

Due to the finding that there was no change in the sensory conditions throughout the trials, it is reasonable that there was no main effect of period ($p = 0.816$). Sway power in the control groups was fairly constant throughout each trial, as seen in Figure 4.12. Although there was a great deal of variance in the patient group, pair wise comparisons revealed no significant difference between the four periods in any subject group.

A significant trial effect ($p < 0.001$) indicated further habituation in the condition 5 trials, with a reduction in power across trial repetitions 1 through 3. Pair wise comparisons revealed significant differences between all three trials when subject types were averaged together. In the young control group, the first repetition differed significantly from the third ($p = 0.043$). The older control group also showed habituation after trial repetition 1, as it differed significantly from the following two trials ($p = 0.003$ and $p = 0.001$, respectively). The main effect of trial was also significant for the patient group ($p = 0.027$), with the largest decrease between trial repetitions 2 and 3 ($p = 0.026$). Table 4.5 provides a summary of the statistical results.

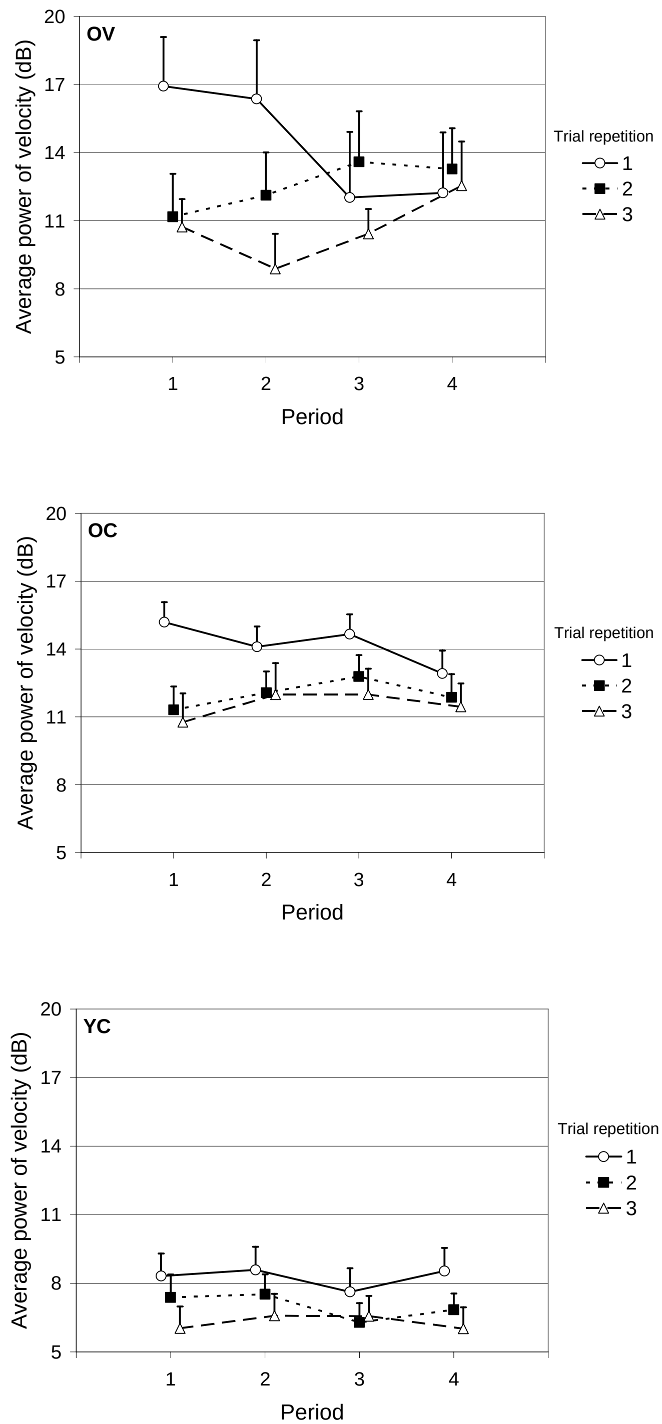

Figure 4.12 Average power of velocity (dB) during four 5 s periods of three control trials. During these trials, the visual scene amplitude was 12 cm and the support surface was sway-referenced (condition 5). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.5 Summary of the ANOVA results for condition 5. Significant effects ($\alpha = 0.05$) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	p-value
trial	**< 0.001**
period	0.816
subtype	**< 0.001**
trial*subtype	0.503
period*subtype	0.366
trial*period	**0.001**
trial*period*subtype	**0.004**

Post hoc: trial repetition	p-value
1, 2	**< 0.001**
1, 3	**< 0.001**
2, 3	**0.035**

Post hoc: subtype	p-value
YC, OC	**< 0.001**
YC, OV	**0.009**
OC, OV	1.000

4.6 CONDITION 6: SWAY-REFERENCED SUPPORT, 4 CM SCENE

Trials 16-18 of the experiment acted as control trials as well, with the support surface sway-referenced and the visual scene amplitude 4 cm for each trial (condition 6). Subject type was the only significant effect ($p = 0.008$), with post hoc analysis showing a significant difference between the control groups ($p = 0.007$). As seen in Figure 4.13, the young controls continued to sway less than the older subjects. A great deal of variability was present in the patient group as seen in the large standard error bars on the plot. As in the previous condition, no adaptation was found (period $p = 0.075$). The effect of trial was also not significant ($p = 0.605$), showing that no habituation occurred. Statistical results are given in Table 4.6.

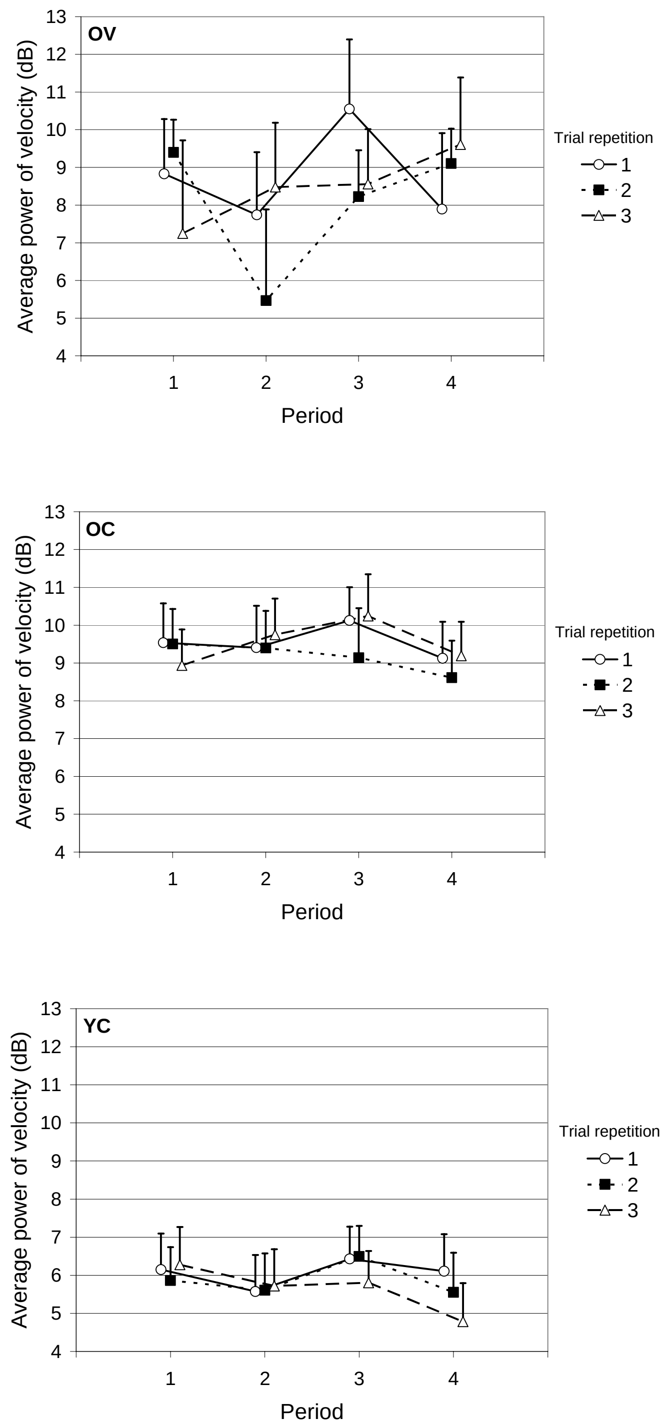

Figure 4.13 Average power of velocity (dB) during four 5 s periods of three control trials. During these trials, the visual scene amplitude was 4 cm and the support surface was sway-referenced (condition 6). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.6 Summary of the ANOVA results for condition 6. Significant effects ($\alpha = 0.05$) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	p-value
trial	0.605
period	0.075
subtype	**0.008**
trial*subtype	0.931
period*subtype	0.416
trial*period	0.298
trial*period*subtype	0.309

Post hoc: trial repetition	p-value
1, 2	-
1, 3	-
2, 3	-

Post hoc: subtype	p-value
YC, OC	**0.007**
YC, OV	0.334
OC, OV	0.911

4.7 CONDITION 7: SWAY-REFERENCED SUPPORT, 4 CM TO 12 CM SCENE AMPLITUDE

A visual scene transition occurred in the seventh condition of the experiment (trials 19-21). While the support platform remained sway-referenced, the amplitude of the scene increased from 4 to 12 cm at a random time between 20 and 30 s into the trial (between periods 2 and 3).

Figure 4.14 shows the instantaneous power of sway velocity averaged over each subject group during the condition 7 trials. Data from the 30 s surrounding the transition (represented by a dotted line) are shown. Increases in sway power appeared primarily in the OC and OV subject groups.

Across all periods and trials, there was a significant subject type effect ($p = 0.001$). The older control group had the greatest amount of sway, followed closely by the patient group (Figure 4.15). The young control group had the least amount of sway (3.80 dB less power than the OC group, $p = 0.002$).

A main effect of period ($p < 0.001$) was found across all subject types with an overall increase in power from periods 1 through 4. The total amount of increase differed significantly based on subject group (period*subtype $p = 0.009$). The increase was significant in OC (3.92 dB, $p < 0.001$) and YC (1.53 dB, $p = 0.023$). There appeared to be an increase in power in the OV group but the effect was not significant (3.92 dB, $p = 0.222$).

The main effect of trial was significant ($p = 0.020$). Post hoc tests showed a significantly greater amount of sway during repetition 1 compared to repetition 3 (1.45 dB, $p =0.005$). This is further evidence for habituation.

As in the other trials with transitions, further analysis was done to compare each set of two consecutive periods. During the first two periods, a period effect was present with increased sway in period 2 ($p = 0.009$) regardless of the fact that the conditions remained constant. In addition, a significant difference in sway power due to subject type was found ($p = 0.025$), in which the older controls had more sway than the younger controls.

As shown in Figure 4.15, there was an increase in sway power from periods 2 to 3 ($p = 0.001$). The effect was dependent on subject type (period*subtype $p = 0.020$), with only the older controls showing increases in all three trials.

Between periods 3 and 4, the power of sway velocity continued to increase ($p < 0.022$), primarily in the older subject groups during the second two repetitions, while the power increased only slightly in the young control group. Overall, there was a main effect of subject type ($p < 0.001$). Post hoc tests showed significant differences between the young subjects and both the older controls ($p < 0.001$) and the older patients ($p = 0.020$).

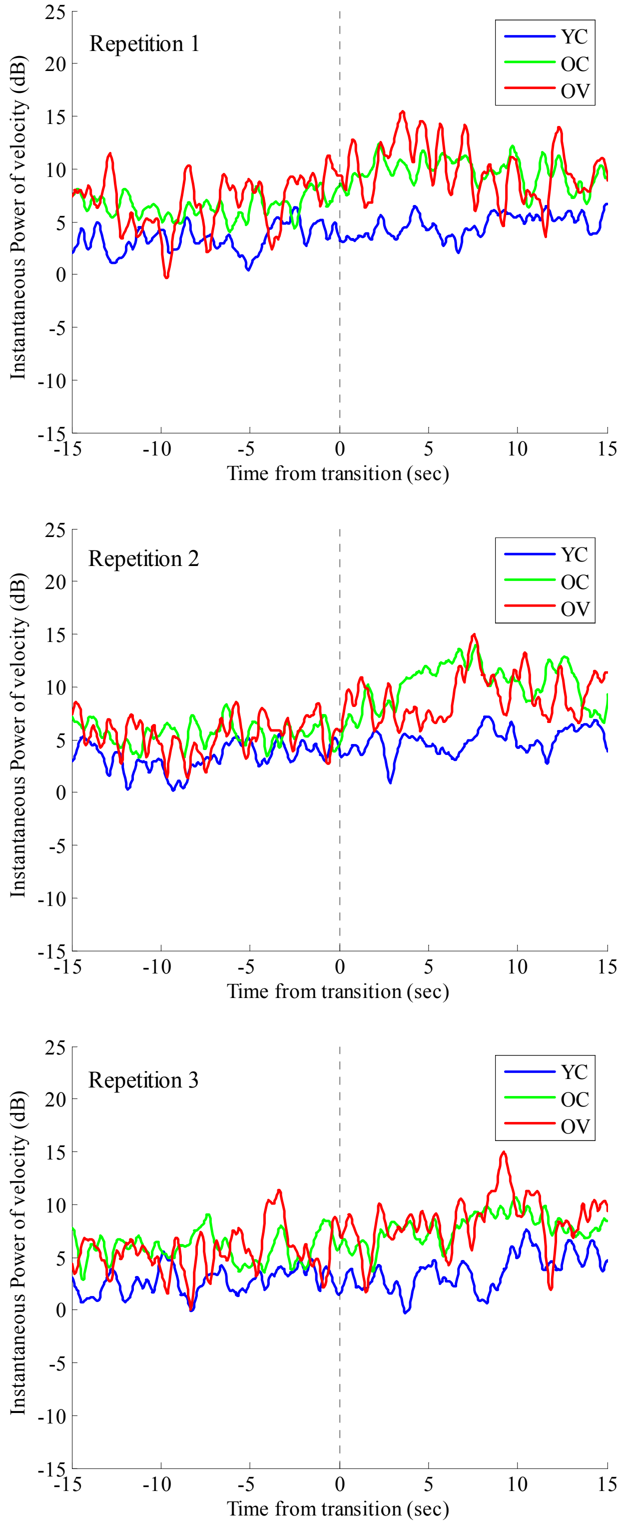

Figure 4.14 Instantaneous power of velocity averaged over each subject group. Trial repetitions are shown in separate plots, as indicated by the repetition number in the upper left-hand corner of each plot.

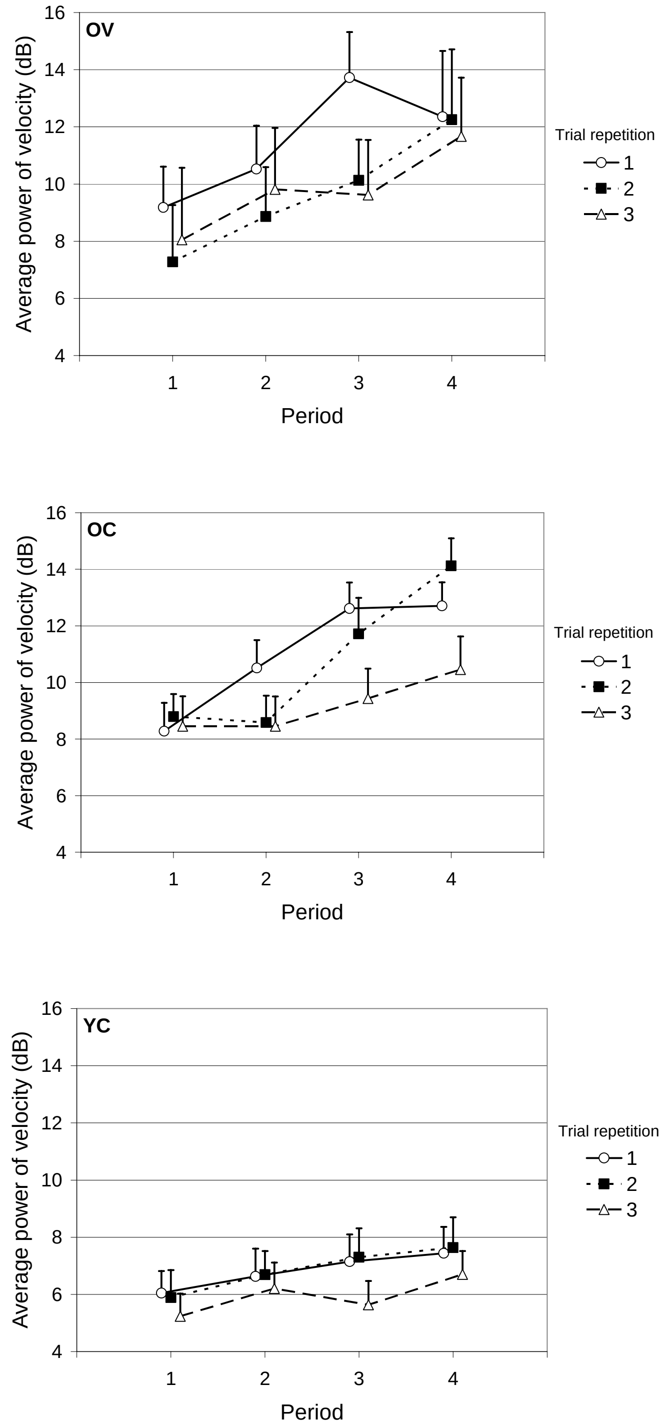

Figure 4.15 Average power of velocity (dB) during four 5 s periods of three transitional trials. During these trials, the visual scene amplitude increased from 4 to 12 cm while the support surface remained sway-referenced (condition 7). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.7 Summary of the ANOVA results for condition 7. P-values with significant effects (α = 0.05) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
trial	**0.020**	0.271	**0.010**	**0.006**
period	**< 0.001**	**0.009**	**0.001**	**0.022**
subtype	**0.001**	**0.025**	**0.002**	**< 0.001**
trial*subtype	0.513	0.836	0.401	0.370
period*subtype	**0.009**	0.676	**0.020**	0.669
trial*period	0.060	0.671	0.112	0.064
trial*period*subtype	0.520	0.288	0.787	0.397

Post hoc: trial	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
1, 2	0.555	-	0.204	0.865
1, 3	**0.005**	-	**0.007**	**0.001**
2, 3	0.331	-	0.552	0.082

Post hoc: subtype	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
YC, OC	**0.002**	**0.034**	**0.003**	**< 0.001**
YC, OV	0.054	0.208	0.053	**0.020**
OC, OV	1.000	1.000	0.999	0.999

Post hoc: period	All periods
1, 2	0.055
1, 3	**< 0.001**
1, 4	**< 0.001**
2, 3	**0.008**
2, 4	**< 0.001**
3, 4	0.123

As in previous trials with changing sensory conditions, further analysis was done to investigate whether the increase in sway power observed after the increase in scene amplitude was due to the transition itself or merely the larger scene amplitude. Period 3 of condition 7 was compared to period 3 of condition 5 (the corresponding control condition). During these periods, the support surface was sway-referenced and the scene amplitude was 12 cm (Figure 4.16). The main effect of trial type was significant ($p = 0.028$). The levels of sway in the control trials were 0.96 dB greater than those in the transitional trials. This effect was greatest in the OC group.

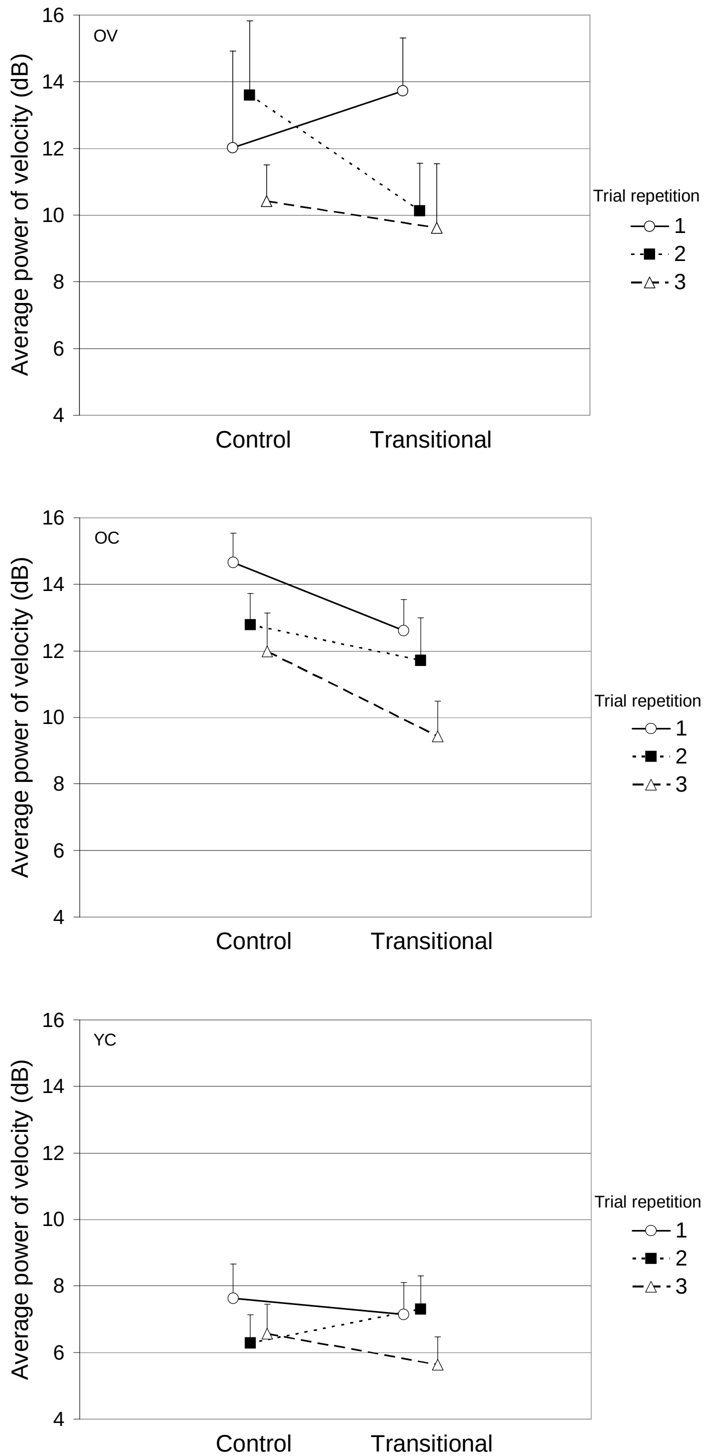

Figure 4.16 Average power of velocity (dB) during period 3 of conditions 5 (control) and 7 (transitional). During these periods, the support surface was sway-referenced and the visual scene amplitude was 12 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

To examine if the power of sway velocity reached baseline levels after the increase in the visual scene amplitude, period 4 of condition 7 was compared to period 4 of condition 5 (Figure 4.17). During both of these periods, the support surface was sway-referenced and the scene amplitude was 12 cm. No trial type effect was observed.

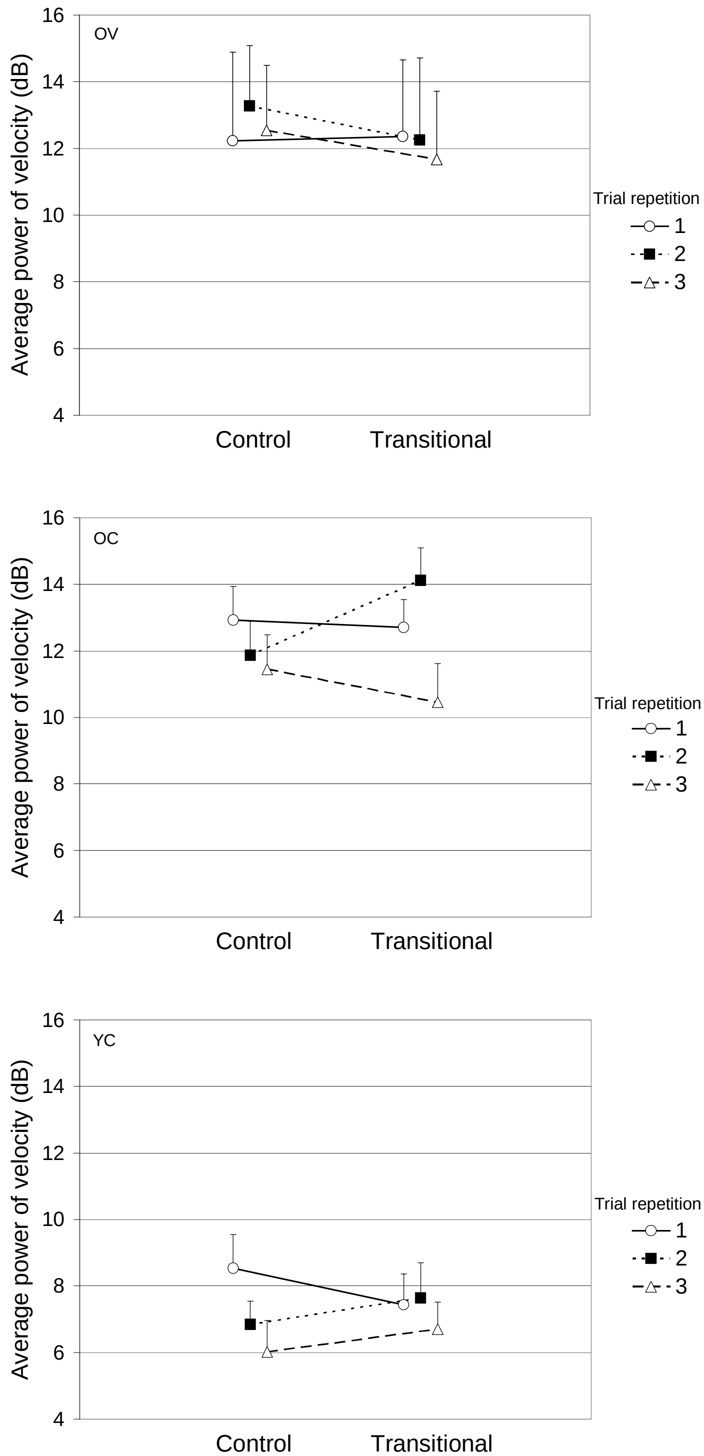

Figure 4.17 Average power of velocity (dB) during period 4 of conditions 5 (control) and 7 (transitional). During these periods, the support surface was sway-referenced and the visual scene amplitude was 12 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

4.8 CONDITION 8: SWAY-REFERENCED TO FIXED SUPPORT, 4 CM SCENE AMPLITUDE

In condition 8, the support platform transitioned from a sway-referenced state to a fixed state mid-way through the trial while the visual scene amplitude was constant at 4 cm. Figure 4.18 shows the instantaneous power of sway velocity averaged over each subject group during the condition 8 trials. Data from the 30 s surrounding the transition (represented by a dotted line) are shown. A clear reduction of sway was observed in all three subject groups.

The average power of sway velocity (dB) is shown in Figure 4.19, with statistical results in Table 4.8. A main effect of subject type was present ($p = 0.001$). Across periods, the YC group had a significantly lower level of sway power than the OC (3.24 dB, $p = 0.003$) and the OV (4.00 dB, $p = 0.018$). There was also a main effect of period ($p < 0.001$), with pair wise comparisons revealing significant differences between all pairs ($p < 0.001$) except periods 1 and 2 ($p = 0.912$). Trial repetition was not significant ($p = 0.404$). All three subject groups showed fairly constant levels of postural sway across all three trial repetitions.

To better characterize the effects of reinserting proprioceptive information, analysis was done comparing each set of two consecutive periods. Subject type was marginally significant in periods 1 and 2 ($p = 0.056$), with young controls swaying less than older subjects. The level of sway power remained fairly steady for all subject types in periods 1 and 2 ($p = 0.333$).

As shown in Figure 4.19, the level of postural sway power decreased from periods 2 to 3 during all trial repetitions and for all subject groups ($p < 0.001$). The decrease was significant for the young controls (3.88 dB, $p < 0.001$) and the older controls (2.83 dB, $p < 0.001$), but not for the older patients (1.44 dB, $p = 0.877$).

Adaptation continued to occur in the fourth period, with significant decreases in power for all three subject groups. The young controls showed the largest amount of adaptation with an average of 3.38 dB less sway power during period 4 than period 3 ($p < 0.001$), while the OV had a 2.83 dB decrease ($p = 0.026$) and the average power of sway dropped 2.04 dB ($p = 0.003$) in the OC group.

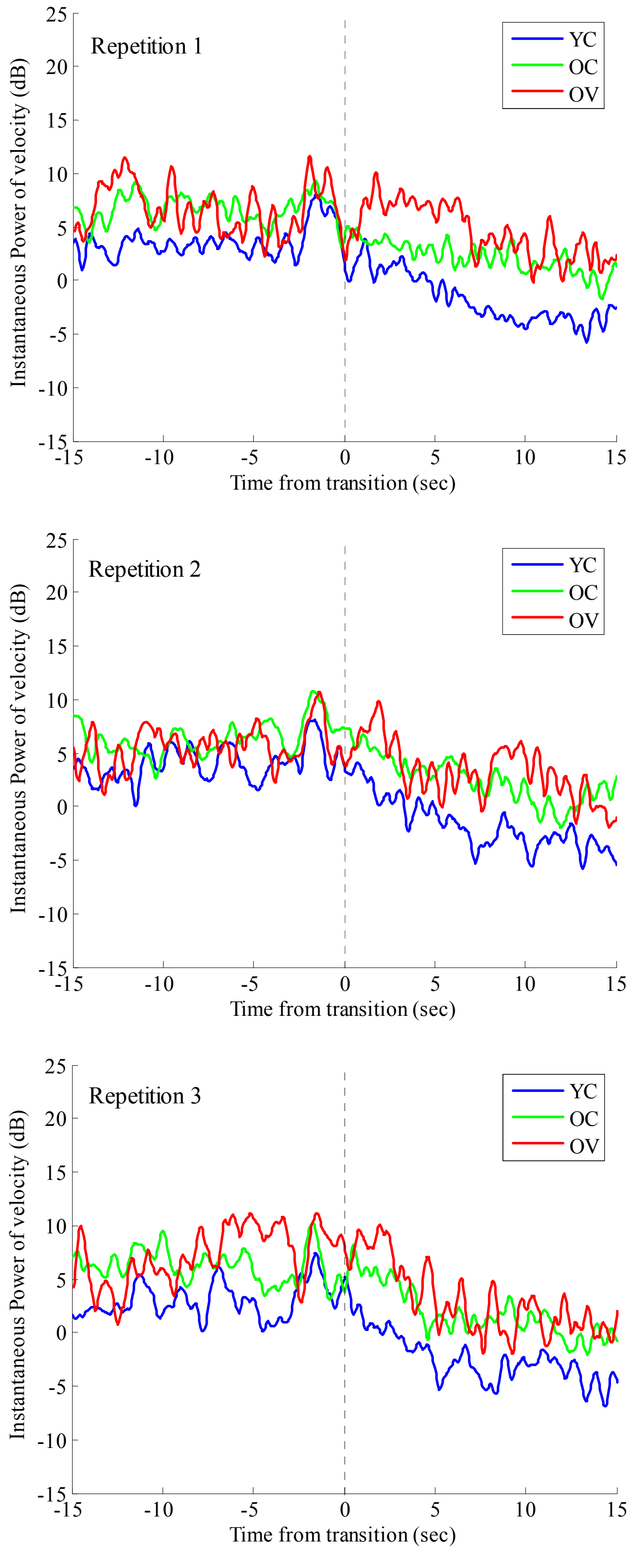

Figure 4.18 Instantaneous power of velocity averaged over each subject group. Trial repetitions are shown in separate plots, as indicated by the repetition number in the upper left-hand corner of each plot.

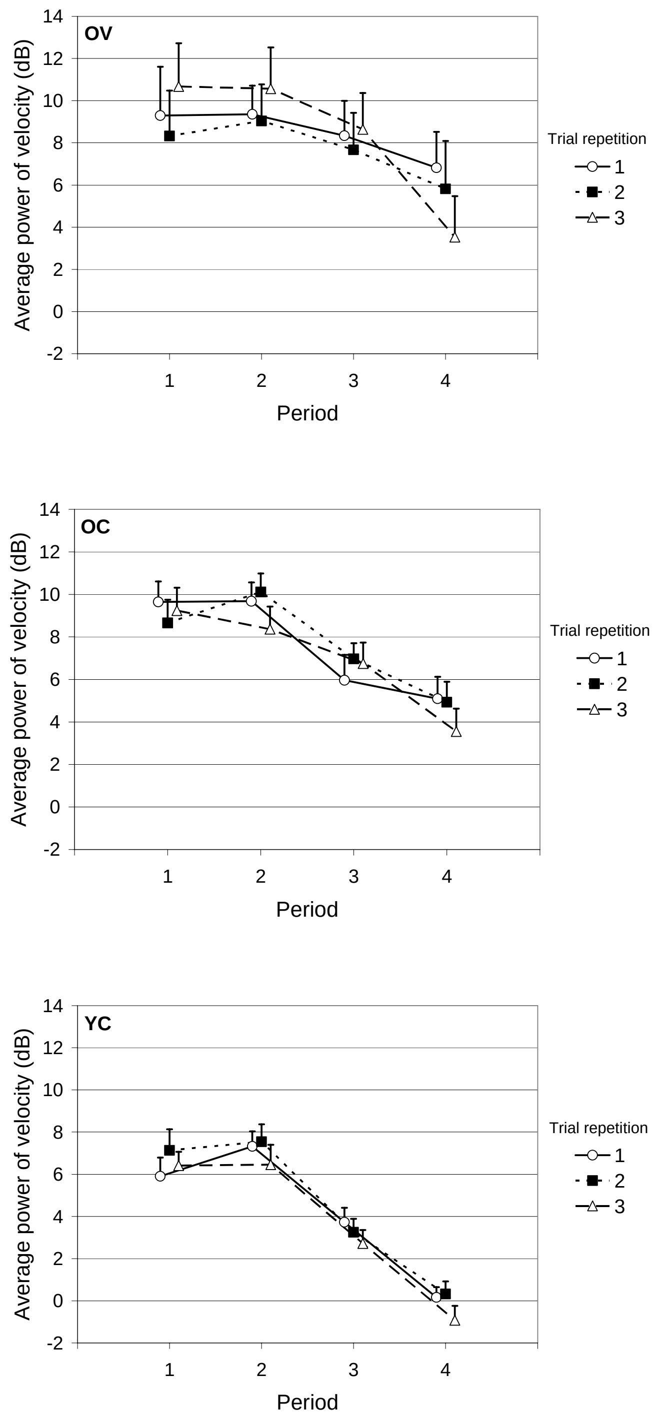

Figure 4.19 Average power of velocity (dB) during four 5 s periods of three transitional trials. During these trials, the visual scene amplitude was 4 cm. The support surface transitioned from sway-referenced to fixed between periods 2 and 3 (condition 8). Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

Table 4.8 Summary of the ANOVA results for condition 8. P-values with significant effects ($\alpha = 0.05$) are indicated in bold. Greenhouse-Geisser values are shown.

Effect	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
trial	0.404	0.945	0.922	0.053
period	**< 0.001**	0.333	**< 0.001**	**< 0.001**
subtype	**0.001**	0.056	**0.004**	**< 0.001**
trial*subtype	0.567	0.199	0.413	0.751
period*subtype	0.113	0.791	0.168	0.123
trial*period	0.061	0.325	0.770	**0.046**
trial*period*subtype	0.331	0.493	0.402	0.423

Post hoc: subtype	All periods	Periods 1 and 2	Periods 2 and 3	Periods 3 and 4
YC, OC	**0.003**	-	**0.013**	**< 0.001**
YC, OV	**0.018**	-	**0.030**	**0.002**
OC, OV	0.931	-	0.874	0.777

Post hoc: period	All periods
1, 2	0.912
1, 3	**< 0.001**
1, 4	**< 0.001**
2, 3	**< 0.001**
2, 4	**< 0.001**
3, 4	**< 0.001**

To investigate whether the decrease in sway power observed after the transition from a sway-referenced platform to a fixed platform was due to the transition itself or merely the fact that the platform was fixed, period 3 of condition 8 was compared to period 3 of condition 2 (Figure 4.20). During these periods, the support surface was fixed and the scene amplitude was 4 cm. There was significantly more sway in the transitional trials (7.92 dB, $p < 0.001$) compared to the control trials.

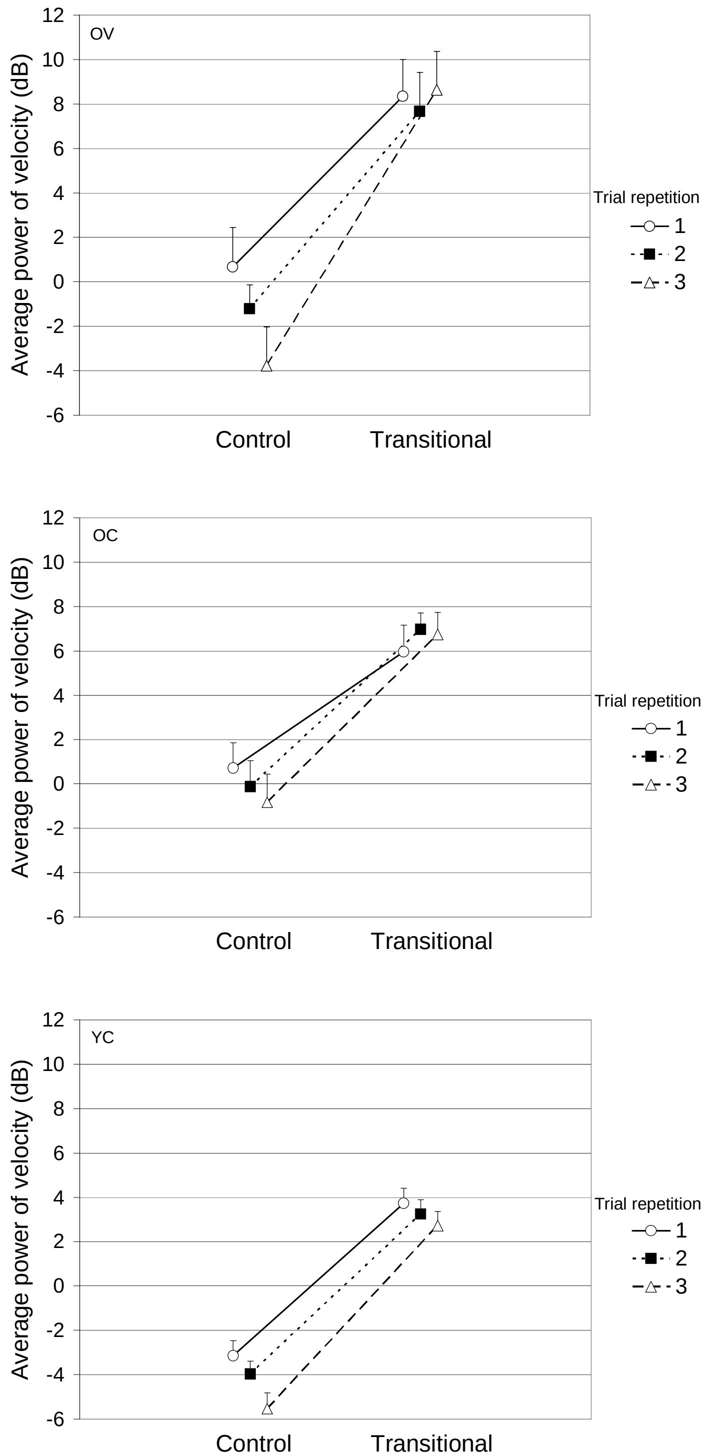

Figure 4.20 Average power of velocity (dB) during period 3 of conditions 2 (control) and 8 (transitional). During these periods, the support surface was fixed and the visual scene amplitude was 4 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

In order to examine if subjects were able to adapt after the increase in scene amplitude to a level of sway comparable to that of the corresponding control trial, period 4 of condition 8 was compared to period 4 of condition 2 (Figure 4.21). During both of these periods, the support surface was fixed and the scene amplitude was 4 cm. The main effect of trial type was significant ($p < 0.001$) with the average sway power in transitional trials exceeding the level in control trials by 5.05 dB, thus indicating that after 10 sec, sway had not returned to baseline levels. An interaction between subject type and trial type was significant, as seen in the smaller difference between trials types in the YC group compared to the OC and OV group (subtype*trial type $p = 0.047$).

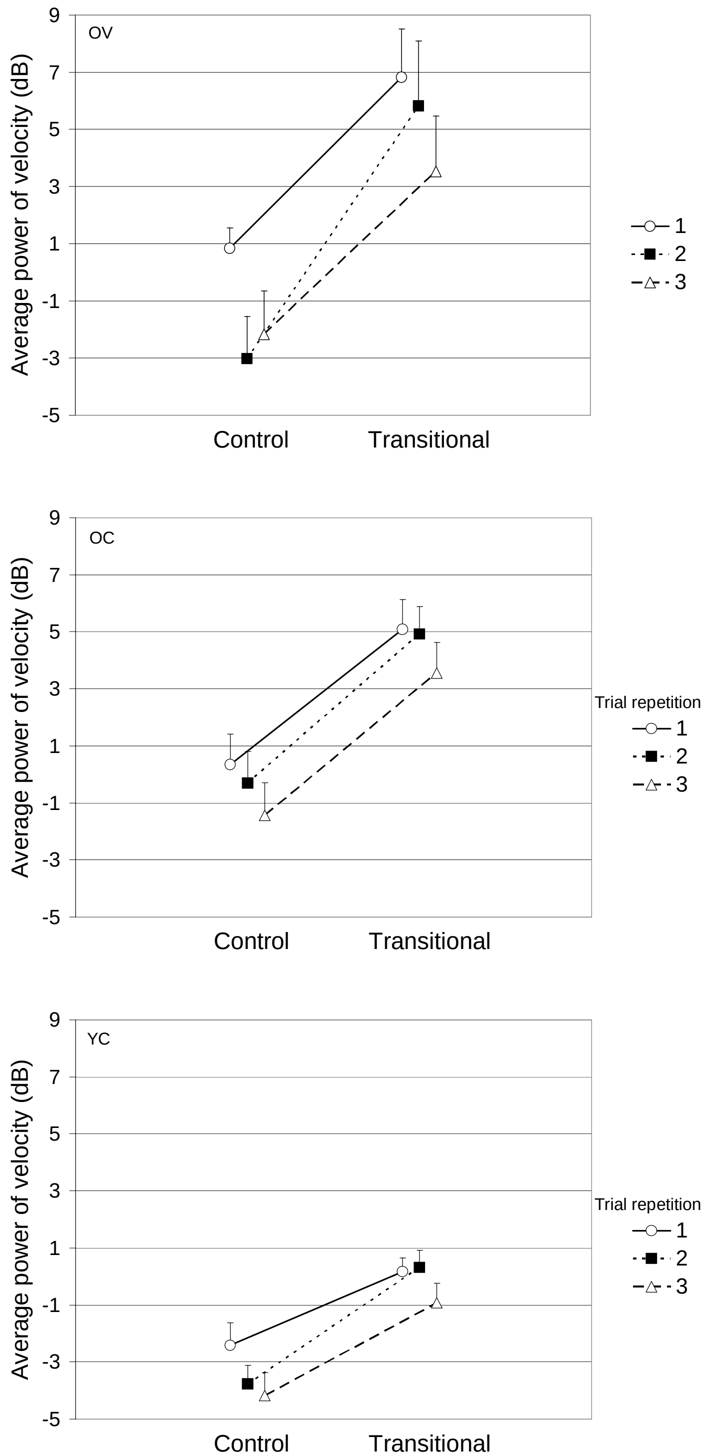

Figure 4.21 Average power of velocity (dB) during period 4 of conditions 2 (control) and 8 (transitional). During these periods, the support surface was fixed and the visual scene amplitude was 4 cm. Results from each of the three subject groups are shown on separate plots. Error bars are the standard error of the mean.

5.0 DISCUSSION

The present research was designed to examine the impact of aging and unilateral vestibular disease on balance as subjects responded to rapid changes in visual and somatosensory input. Sensory integration is a dynamic process: changes in postural sway response occur both between trials and within trials. By studying the time-varying characteristics of postural sway in subjects exposed to transitions in their sensory input, we gained further insight on the process of sensory integration in older adults with and without unilateral vestibular disease.

Participants completed 24 experimental trials: 6 contained an increase in the amplitude of the sinusoidally moving visual surround, 6 contained a change in the amount of proprioceptive information available using a sway-referenced force platform, and 12 acted as control trials. The average power of head AP velocity was studied in three subject groups: young controls, older controls, and older people with unilateral vestibular disease. Statistical analysis focused on the between-subject differences as well as the time-varying characteristics of postural sway.

5.1 CONDITION 1: FIXED SUPPORT, 12 CM SCENE AMPLITUDE

The first three trials of the experiment acted as control trials for condition 3. In addition to comparing the levels of postural sway during these trials to those of the third condition (section 4.3), observations were made concerning both the effect of age and vestibular function on balance as well as the time-varying characteristics of sway during steady-state conditions, i.e. when no transitions were present.

As described in section 4.1, the three subject groups displayed significantly different powers of postural sway velocity during the first condition. The older controls had the greatest amount of sway power, followed by the older vestibular patients and finally the young controls. The difference in sway levels for the two older subject populations did not differ significantly. These results agree with previous findings comparing postural sway levels among different age groups. There is a general consensus that humans tend to exhibit greater postural instability with increasing age (Overstall, Exton-Smith et al. 1977; Dornan, Fernie et al. 1978; Wolfson, Whipple et al. 1992; Cohen, Heaton et al. 1996; Baloh, Corona et al. 1998a; Baloh, Jacobson et al. 1998c). It is also accepted that while postural sway increases in all subjects while viewing optic flow, the increase is the greatest in older adults (Ring, Matthews et al. 1988; Sundermier, Woollacott et al. 1996; Borger, Whitney et al. 1999).

Our finding that the OV group had high levels of postural sway power is in agreement with previous studies suggesting that people with vestibular disorders have an increased sensitivity to optic flow (Redfern and Furman 1994; Peterka and Benolken 1995; Loughlin, Redfern et al. 1996; Sundermier, Woollacott et al. 1996). People with vestibular deficits typically regain their balance function over time as their visual and proprioceptive senses begin to compensate for their vestibular loss. This greater reliance on visual information leads to an increased sensitivity to optic flow (Dornan, Fernie et al. 1978; Black, Shupert et al. 1989; Lacour, Barthelemy et al. 1997).

The lack of difference in the magnitude of sway velocity power between the older subject populations is consistent with the data of Sparto et al. (2006), who showed that age has a greater effect on optic flow-induced sway than the presence of unilateral vestibular disease (Sparto, Furman et al. 2006). However, it is also possible that no effect was found due to the small sample of OV subjects. The same general relationship between sway levels in young subjects compared to older subjects was present in all conditions and was thus not dependent on sensory conditions.

The significant effect of period in the first three trials suggested the presence of adaptation. In the first repetition, all three subject groups showed decreases in the power of their sway over time. In the second and third repetition, this decrease was most prevalent in the older control group. A great deal of research has suggested that the characteristics of postural sway change over time intervals on the order of 10 seconds (Carroll and Freedman 1993; Schumann, Redfern et al. 1995; Loughlin, Redfern et al. 1996; Perrin, Schneider et al. 1998; Loughlin and Redfern 2001; Loughlin, Redfern et al. 2003). The changes in postural responses in time differ between subject groups. For instance, the OC group showed greater amounts of adaptation than the OV group. This finding is in agreement with the data obtained by Loughlin and Redfern et al. (1996), who found that people with vestibular deficits are not able to adapt to constant frequency optic flow to the extent seen in healthy subjects (Loughlin, Redfern et al. 1996). Contrary to Loughlin and Redfern (1996), large amounts of adaptation were not seen in the YC group. It is possible that this is because their initial levels of postural sway power were much less than those for the older groups.

The last hypothesis of the present study was that habituation would occur in all subject groups but to a greater extent in the healthy participants. Evidence of habituation was seen in all three subject groups during condition 1. Figure 4.1 shows a clear decrease in the power of postural sway during successive repetitions for all subject groups. The greatest amount of habituation occurred between the first and second trials. Previous studies have seen similar patterns of habituation using a variety of stimulation types including visual surround motion, with the largest decrease in sway occurring from trial 1 to trial 2 (Bronstein 1986; Mahboobin, Loughlin et al. 2005).

5.2 CONDITION 2: FIXED SUPPORT, 4 CM SCENE AMPLITUDE

The condition 2 trials acted as control trials for comparison with condition 8 (section 4.8). The visual scene moved sinusoidally with a 4 cm amplitude, in contrast to the 12 cm amplitude of condition 1.

All three groups had greatly reduced levels of postural sway power during the condition 2 trials compared to condition 1. There are two possible explanations for this. First, it is possible that the subjects habituated to the optic flow and reduced their visual feedback gain during the first few trials. This would cause an overall lower amount of sway in ensuing trials. Second, the reduced levels of sway could be attributed to the smaller visual scene amplitude. The reduced sway is likely due to some combination of the two factors. However, due to the large reduction in sway between the last trial of condition 1 and the first trial of condition 2, it is likely that the effect is mostly due to the decrease in visual scene amplitude between conditions 1 and 2. It is possible that if the 4 cm optic flow trials had been conducted first, greater sway would have been elicited in condition 2 compared to condition 1. The rationale for having the conditions in the same order for all subjects was so that there would be an equal basis for comparing the sway obtained in the transitional trials to the sway from the control trials in all subjects. Furthermore, the 4 cm control trials for condition 2 needed to be conducted immediately before the first perturbation trial of condition 3, in which the optic flow stimulus increased from 4 to 12 cm, so that only one factor was changing.

This explanation fits well with findings in previous research that the magnitude of sway is dependent on the amplitude of scene movement. Lestienne and Soechting et al. (1977) found that postural sway deviations are proportional to the logarithm of the visual motion amplitude

(Lestienne, Soechting et al. 1977). Borger and Whitney et al. (1999) also found a direct relationship between scene and sway amplitude (Borger, Whitney et al. 1999).

In contrast to the results of condition 1, no adaptation was observed in any of the subject groups. It is possible that most of the adaptation to the visual stimulus occurred in the first few trials. It may also be that because the original levels of sway were fairly low in comparison to those in condition 1, there was less room for adaptation.

Further habituation took place during the second condition, with the majority occurring between the first two trial repetitions. These findings are consistent with those in condition 1.

5.3 CONDITION 3: FIXED SUPPORT, 4 CM TO 12 CM SCENE AMPLITUDE

The third condition of the experiment contained an increase in the amplitude of the visual scene between periods 2 and 3 while the force platform remained fixed. Before the transition, the levels of postural sway power remained fairly constant in all subject groups, though the OV group showed a high degree of variability. As expected, following the increase in scene amplitude, there was an increase in sway power from periods 2 to 3. This increase appeared mainly in the OC and OV groups, with older controls showing slightly larger increases than older vestibular patients. This provides partial support for the second hypothesis, which stated that increasing the amplitude of the visual scene would result in an increase in sway power in all subject groups, especially those with unilateral vestibular disease. The finding that the older controls were more affected by the change in optic flow suggests that they may be more visually dependent than the vestibular patients.

It has been hypothesized that as people age, sensory information becomes inaccurate, leading to greater difficulty in the processing of information from the sensory systems contributing to balance. As a result, older adults both with and without vestibular deficits may have a difficult time adjusting to new sensory conditions. This idea is supported by our findings.

Several other researchers have found similar age-related differences. For instance, Teasdale and Stelmach et al. (1991b) studied the postural sway responses in older and younger adults submitted to successively reduced and augmented visual sensory conditions. The older subjects responded with increased sway when visual information was both removed and reinserted, in contrast to the increase experienced by the young subjects only when visual information was removed (Teasdale, Stelmach et al. 1991b). Similarly, Simoneau and Teasdale et al. (1999) found that suddenly changing a subject’s focal point through the use of elevator-like doors resulted in two to three times more COP range and speed in the older subjects than the younger subjects (Simoneau, Teasdale et al. 1999).

No adaptation was observed in the 10 s following the transition to a higher scene amplitude. Rather, the power of sway velocity from periods 3 to 4 continued to increase, primarily in the older subject groups during the first two trial repetitions. By the third repetition, the older subject groups maintained a fairly constant level of sway power following the transition. This suggests that the time course for adaptation to the new sensory environment was longer than 10 s for the older subjects. It also suggests that learning was occurring over like trials, leading to a faster rate of adaptation.

Very little habituation occurred in the third condition. Though the trials were found to be significantly different, it was mainly due to the finding that by the third repetition, the older subjects had begun to adapt to the increase in scene amplitude within the 10 s after the transition.

To determine whether the increase in sway following the transition was caused simply by a larger optic flow amplitude rather than the presence of the transition, period 3 of the third condition was compared to period 3 of the first condition. As shown in Figure 4.5, the sway power was greater in the control trials than in the transitional trials. This finding is most likely attributed to the fact that condition 1 was the first condition that the subjects experienced on this testing day. The levels of postural sway were thus abnormally high as the subjects adjusted to the sensory mismatch produced by the optic flow. Thus, it cannot be determined whether the increase in sway found after the transition was due to the actual transition or the larger visual scene amplitude.

In order to examine if subjects were able to adapt after the transition to a level of sway comparable to that of the corresponding control trial, period 4 of condition 3 was compared to period 4 of condition 1. As seen in Figure 4.6, the levels of sway following the transition were lower than those in the control trials. This is again thought to be due to the particularly large amounts of sway present in the first three trials of the experiment. Thus it is not clear if baseline levels would have been met if the trial order had been altered.

5.4 CONDITION 4: FIXED TO SWAY-REFERENCED SUPPORT, 4 CM SCENE AMPLITUDE

In the fourth condition, the platform transitioned to a sway-referenced state in the middle of the trial. This was the first time the subjects experienced a change in the reliability of their somatosensory information on this testing day. However, all subjects had previously experienced both the sway-referenced platform as well as optic flow in a prior experiment. As was the case in condition 3, the pre-transition levels of sway were fairly steady for each subject group. Directly following the transition, all three groups showed a clear disturbance resulting from the change to a sway-referenced platform as seen by the large increases in sway velocity from periods 2 to 3. This is in support of the first hypothesis, which stated that following a decrease in reliable somatosensory input, all subjects would show an increase in postural sway power.

Though increases were found in all trials, the magnitude of increase depended on both the subject type and the trial repetition (Figure 4.9). In the first repetition, the OV group had the largest increase in sway from periods 2 to 3, followed by the young controls and then the older controls. This is only in partial agreement with the second hypothesis, which stated that the increase in sway power would be greatest in older vestibular patients followed by older controls. A possible explanation for this effect is that older and younger control subjects have similar sway velocity saturation thresholds in these conditions, and that both OC and YC subjects groups reached this threshold during trial 1. This idea is supported by findings from Peterka and Benolken (1995). They investigated the influence of bilateral vestibular loss (BVL) on postural sway elicited by optic flow. Healthy subjects demonstrated a saturation of postural sway at large amplitudes of scene movement, whereas subjects with BVL did not (Peterka and Benolken

1995). Sensory re-weighting could account for this nonlinearlity, with control subjects showing increased reliance on vestibular information as visual information became increasingly unreliable. The effective increase was larger in YC subjects compared to OC subjects because they had a lower initial level of sway power. In the second repetition, the OV group continued to have the largest increase, while there was no difference between the control groups. Finally, all subject groups had roughly equal magnitudes of response to the transition in the third repetition.

Post-transition adaptation was seen in all subject types, though the effect was only significant in the control groups. Figure 4.7 provides detail concerning the time course of adaptation in the 15 s after the transition. A decrease in sway over time was clear in both the YC and OV groups during the first repetition. In the second repetition, adaptation appears to be present in all three groups, while in the third repetition, it is largely absent. The finding that a lack of adaptation was found in the OV group in the statistical analysis may be due to the large amount of variance and small sample size of this group. The third hypothesis of the study stated that the process of adaptation following a somatosensory transition will take longer in older subjects then younger subjects, especially when the older subjects have a vestibular deficit. Though it is difficult to quantify the speed of adaptation, the finding that a significant decrease in sway was not seen in the OV group may be evidence that the length of time for OV subjects to adapt was longer than the 13 s post-transition analyzed statistically.

As in condition 3, further analysis was done to address whether the increase in sway following the transition was due to the transition itself or the fact that the platform was sway-referenced. Figure 4.10 shows the average power of sway velocity during period 3 of condition 4 compared to period 3 of condition 6. During both of these periods, the platform was sway-referenced and the scene amplitude was 4 cm. It is clear that there was significantly more sway during the transitional trials, suggesting that the increase in sway was due to the transition as opposed to the state of the support surface.

Period 4 of condition 4 was then compared to period 4 of condition 6 to study the extent to which subjects were able to approach the baseline levels of sway seen in corresponding control trials. The effect of trial type was found to be significant, with more sway appearing in trials that contained transitions, especially in the first trial repetition. By the third repetition, adaptation was sufficient for the subjects to reach levels of sway comparable to those found when no transition occurred.

5.5 CONDITION 5: SWAY-REFERENCED SUPPORT, 12 CM SCENE AMPLITUDE

Condition 5 was designed to be the control for condition 7 in order to investigate the effects of an increase in visual scene amplitude on a sway-referenced platform (section 4.7). The support surface was sway-referenced and the scene amplitude was 12 cm during each trial. Further comparisons were also made between this condition and the first condition to investigate the effect of reducing proprioceptive information on postural stability. While the movement of the optic flow was the same during both conditions, the platform movement differed. After averaging across subjects, periods, and trials, it was found that the amount of sway when the platform was sway-referenced was 6.61 dB greater than the amount of sway when the platform was fixed.

The finding that a higher level of postural sway was present in all subject groups during trials in which proprioceptive information was unreliable is in agreement with previous findings showing greater instability when somatosensory cues are reduced (Black, Wall et al. 1983; Teasdale, Stelmach et al. 1991a; Peterka and Benolken 1995; Baloh, Jacobson et al. 1998b; Baloh, Jacobson et al. 1998c; Borger, Whitney et al. 1999). For instance, Peterka and Benolken (1995) found that the amplitude of AP postural sway could increase by a factor of 4 in both control subjects and subjects with bilateral vestibular loss when the support surface was sway-referenced compared to when it was fixed (Peterka and Benolken 1995).

In contrast with condition 1, no adaptation was found in condition 5. It is possible that subjects had already adapted to these conditions during the time prior to the 20 s analyzed. Furthermore, subjects had already experienced several trials of the 12 cm optic flow stimulation, as well as the sway-referenced platform. However, habituation was present for all subject groups, with the greatest decrease seen in the OV group and the smallest decrease in the YC group. Though habituation was expected in the control groups, it was predicted to occur to a lesser extent in the OV group. Possible reasons for the larger habituation in the OV group include the large initial amount of sway in trial 1 for the older subjects with vestibular deficits and the relatively small initial levels of sway seen in the control groups.

5.6 CONDITION 6: SWAY-REFERENCED SUPPORT, 4 CM SCENE AMPLITUDE

The sixth condition acted as a control for condition 4 (section 4.4). The levels of sway in this condition were also compared to those of conditions 2 and 5 to observe the effects of the platform state and the scene amplitude, respectively. During conditions 6 and 2, the scene amplitude was the same but the platform condition was different. A total of 9.62 dB more sway power was seen in the trials in which the platform was sway-referenced compared to when it was fixed. This is consistent with the findings described in section 5.5.

During conditions 6 and 5, the platform was sway-referenced but the scene amplitude was different. In the trials in which the scene amplitude was 12 cm (condition 5), there was an average of 2.87 dB more sway than when the scene moved with a 4 cm amplitude. This is in agreement with the findings discussed in section 5.2, in which a large amplitude of optic flow was associated with a greater amount of sway.

No adaptation or habituation was observed for any of the subject groups during condition 6. This is possibly due to the fact that these experimental conditions were well practiced.

5.7 CONDITION 7: SWAY-REFERENCED SUPPORT, 4 CM TO 12 CM SCENE AMPLITUDE

Condition 7 contained the second set of visual perturbations, this time on a sway-referenced surface. There was a general trend for the power of sway velocity to increase over time in all three subject populations. This increase was mostly between periods 2 and 3, when the visual scene amplitude increased to 12 cm. This corresponds with the results from condition 3, in which a larger scene amplitude induced a greater amount of postural sway. In addition, the increase was the greatest in the older subject groups. This is further support for the second hypothesis, which stated that following an increase in the amplitude of the visual scene, an increase in sway power would occur in all subject groups, especially in the older subjects.

Contrary to the expectations described in the second hypothesis, the increase in the power of sway velocity following the change in visual information was greater in the control group then in the vestibularly impaired group. As in condition 3, the control subjects seemed to be more visually dependent than the patients. It is interesting to compare this finding with condition 4, in which the OV group experienced greater instability following the transition to a sway-referenced platform, thus inferring that the patients are more dependent on proprioceptive information.

The power of postural sway increased during the 10 s following the visual perturbation, primarily in the older subject groups during repetitions 2 and 3. This increase was only significant for the older control group. It was expected that adaptation would occur following the initial increase in sway power after the transition. It is possible that the time course of adaptation was too long to be observed in the 10 s included in the statistical analysis.

Although a main effect of trial was present in condition 7, significant habituation only occurred in the older control group. The lack of habituation in the young control group may be due to the finding that the level of sway during the first repetition was fairly low, so it was not possible to have a large decrease in the following repetitions. It is apparent that the variance in the sway power of OV subjects contributed to lack of habituation.

To determine whether the increase in sway after the transition was due to the transition itself or simply due to the large scene amplitude, period 3 of condition 7 was compared to period 3 of condition 5, using the same reasoning as in section 5.3. The average amount of sway power in the transitional trials was significantly less than in the control trials, especially in the OC group. It is surprising that subjects had a lower power of sway velocity following a visual perturbation than they did when no perturbation was present. This suggests that the large amount of postural sway in period 3 may have been due to the large scene amplitude rather than the transition. The finding that the amount of sway was lower than in the control trials shows that throughout the experiment, subjects were able to acclimate to the optic flow and decrease their postural sway velocity. In other words, habituation occurred not only within identical trials, but also throughout the entire experiment.

No significant difference was found between period 4 of condition 7 and period 4 of condition 5, as described in section 4.7. This implies that subjects were able to reach baseline levels of sway found in control trials during the 10 s following the perturbation. The finding that baseline levels were reached during trials in which the transition was in the visual information but not in the somatosensory information may be due to the larger increases seen following the change from a fixed to sway-referenced platform compared to those seen when the scene amplitude increased.

5.8 CONDITION 8: SWAY-REFERENCED TO FIXED SUPPORT, 4 CM SCENE AMPLITUDE

During the eighth condition of the protocol, proprioceptive information was reinserted as the support surface transitioned from sway-referenced to fixed. Following the transition, a decrease in the power of sway velocity was seen in all subject groups and trial repetitions. The effect was the greatest in the YC group, followed by the OC group. Though a small decrease was seen in the OV group, it was not found to be significant. This is consistent with the expectations of the second hypothesis. Further decreases in sway power were present between the third and fourth periods, as seen in both the time marginals and the statistical analysis (Figures 14.18 and 14.19, respectively).

According to previous studies that have examined a transition from a sway-referenced to a fixed platform, the reinsertion of accurate proprioceptive information caused a temporary increase in postural sway (Teasdale, Stelmach et al. 1991b; Hay, Bard et al. 1996; Simoneau, Teasdale et al. 1999; Peterka and Loughlin 2004). Feedback models of postural control demonstrated that this effect could be caused by an incorrect torque generation based on the previous level of available somatosensory input. Although transient increases in sway power appeared in condition 8, particularly in the first and second repetitions, they occurred during the 3 s in which the support platform transitioned to a fixed state. It is unclear whether these increases in power were due to incorrect torque generation or were merely an effect of the ramping of the force platform back to a level position.

The third periods of conditions 8 and 2 were compared with each other to examine whether the decrease in sway following the reinsertion of proprioceptive information was due to the transition itself or merely the current fixed state of the platform. Statistical analysis revealed significantly more sway power during the transitional trials, implying that the increased sway in period 3 of condition 8 was due to the change in the state of the platform.

Significantly more sway was observed in the fourth period of condition 8 than the corresponding period of condition 2. This indicates that subjects were not able to reach the baseline levels of sway present in the corresponding control trials within 10 s. As shown in Figure 4.18, sway continued to decrease for at least 15 s following the transition. Thus it is possible that by the end of the trial, sway had reached baseline levels.

6.0 CONCLUSIONS

By studying the time-varying characteristics of postural sway in subjects exposed to transitions in their sensory input, we gained further insight on the process of sensory integration in older adults with and without unilateral vestibular disease.

Both older controls and older people with vestibular deficits were observed to sway more than healthy younger subjects during all experimental conditions. Following a decrease in reliable somatosensory input, all subjects showed an increase in postural sway power. This increase was greatest in older subjects with UVH. Upon reinsertion of somatosensory input, all subjects showed a decrease in postural sway. However, this gradual decrease was the least in the older subjects with unilateral vestibular hypofunction. Increasing the optic flow amplitude consistently resulted in increased postural sway power. This effect was mainly seen in the older subject populations.

Adaptation was seen in all subject groups after the removal of reliable somatosensory information, though the effect was only significant in the control groups. The finding that a significant decrease in sway was not seen in the group of subjects with UVH may reflect evidence that they have a longer time-course of adaptation. Adaptation was also present following the reinsertion of somatosensory information, especially in the control subjects.

Little adaptation was observed in the 10 s following transitions to a larger scene amplitude. Rather, the power of sway velocity continued to increase, primarily in the older subject groups. Also this could signify that the time course for adaptation is longer than 10 s following a change in visual information, it could also be viewed as further evidence that the increased sway seen following the visual amplitude change was due to the fact that the optic flow had a larger movement rather than the fact that there was a transition.

Following changes in the reliability of somatosensory input, subjects were unable to adapt to baseline levels of sway found in control conditions within 10 s. However, subjects were generally able to reach these baselines after a change in visual information. This may be due to the smaller increase in sway velocity induced by the visual scene amplitude change.

Habituation was seen in most trial conditions, especially between the first and second presentations of a stimulus. The older controls typically showed the greatest amount of habituation. Although the effect was present in the OV group, it was typically not significant. The lack of habituation in the YC group was attributed to the low initial levels of sway.

The results indicate that older subjects with vestibular disease have an increased level of difficulty maintaining stability when the sources of information contributing to postural control are reduced or unreliable. Under some sensory conditions, this instability is also experienced by healthy older adults. Additionally, older adults with vestibular disease show a lesser ability to adapt to new sensory conditions. It is possible that this contributes to the increased occurrence of falls in older adults both with and without vestibular deficits.

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