ABSTRACT

Title of thesis: THE USE OF VISION IN CHILDREN'S POSTURAL CONTROL

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The purpose of the current thesis was to characterize age-related changes in postural control with variations in the properties of a dynamic visual stimulus. In the first study, seven 4-year-olds, seven 6-year-olds, and seven adults were presented with a visual stimulus that oscillated at 0.1, 0.3, and 0.5 Hz. Results showed the postural response amplitude and timing depended upon stimulus frequency and a reduction in the amplitude response variability indicated increased response precision with age. In the second study, ten 4-year-olds, ten 6-year-olds, and ten adults were presented with a visual stimulus that oscillated at 0.3 Hz, with amplitudes of 0, 2, 5, and 8 mm. The results characterized the response as a utilization of sensory information for postural control, with increased response precision with age. These findings indicate that the visuomotor coordination needed for postural control shows age-related improvements, consistent with the notion of a response tuning.

The Use of Vision in Children's Postural Control

by

Stephen J. Kim

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CHAPTER I

INTRODUCTION

All movements such as sitting, crawling, walking and reaching are embedded within a support structure provided by postural control. Postural control utilizes sensory information from visual, vestibular and somatosensory inputs in an integrated fashion to maintain a stable relationship between the body itself and the environment (Horak & Macpherson, 1996). Researchers have conceptualized motor skill development as an increased stabilization or coordination of this perception action relationship (Barela, Jeka, & Clark, 2003; Bertenthal, Rose, & Bai, 1997; Metcalfe & Clark, 2000) and have assessed this relationship by observing the effects of varying sensory input on movement responses. One experimental paradigm that has been employed to characterize this relationship is the "moving room" paradigm in which the effects of dynamic visual stimulation on postural responses are studied.

In the moving room paradigm, a participant stands on a stationary floor where the visual environment translates with respect to the floor. Movement of the room towards the participant gives visual information suggesting forward sway, which elicits compensatory sway in the direction of the room's movement (Lishman & Lee, 1973). Infants and even neonates have shown some directionally appropriate postural responses to a dynamic visual stimulus, suggesting that they perceive optic flow information and their sways are influenced by it (Delorme, Frigon, & Lagace, 1989; Foster, Sveistrup, & Woollacott, 1996; Jouen, 1988; Butterworth & Hicks, 1977). Bertenthal et al. (1997) showed improvements in the response to an oscillating visual stimulus with experience and suggested that these changes lie within the ability to scale sensory information to the motor response. These changes were evident in the increased precision to the dynamic stimulus, described as “response tuning”. However, previous studies have focused on the changes occurring during infancy and have not addressed early childhood, where a transition period in the use of sensory information for the control of posture has been hypothesized (Shumway-Cook & Woollacott, 1985). This hypothesis suggests that early in the transition period vision dominates postural control whereas later, multiple sensory inputs are integrated to maintain balance. An examination of the developmental changes in the response tuning to a single dynamic visual stimulus may provide a first window to explore this hypothetical transition period in postural control development. Therefore, to better understand the development of vision’s role in postural control, previous work needs to be extended to examine the moving room response in young children.

The goal of the current thesis, therefore, is to characterize the age-related changes in the use of vision for postural control in children four and six years of age by examining the variations in their responses to a dynamic visual stimulus. Manipulations of the frequency and amplitude of the stimulus were used to analyze its effect on the postural response amplitude and timing, along with the stability of these parameters.

The thesis is organized into six chapters. This introduction chapter is the first. The second chapter presents a literature review related to vision’s role in the development of postural control. The third chapter describes the first experiment in which the participants were presented with a visual stimulus that oscillated at frequencies of 0.1, 0.3, and 0.5 Hz. The fourth chapter describes the second experiment in which the visual stimulus frequency was kept constant at 0.3 Hz, while stimulus amplitudes varied from static, 2, 5, and 8 mm. Both of these chapters include the rationale, methods, results, and discussions for each experiment. The last two chapters offer a general discussion of the experimental findings and suggestions for further research.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this chapter is to review the literature related to the development of vision's influence on postural control. This chapter is divided into three main sections. The first section discusses upright postural control, the second section reviews the use of vision for postural control, and the final section discusses the development of visuomotor responses in posture.

Postural Control

The successful execution of a motor task demands postural control of the body's center of mass to maintain a desired limb position. Posture is defined as the position of the body segments in space and against gravity, a definition that includes equilibrium and orientation (Horak & McPherson, 1996). A state of postural equilibrium is achieved when all forces acting on the body are balanced in a manner so that a desired static or dynamic position and orientation is allowed. Postural orientation is the relative position of the body segments with respect to themselves and the environment (Horak & McPherson, 1996). In order to achieve the equilibrium and orientation goals, it is hypothesized that the postural control system creates a representation or estimation of the body's spatial bearings relative to the environment, and makes corrective forces based upon this representation to achieve a desired position (Gurfinkel, Levik, Semetanin, & Popov, 1988; Massion, 1998). The utilization of a spatial orientation representation is consistent with conceptions of the postural control system (Jeka, Oie, & Kiemel, 2000). This representation requires information provided by the integration of information from three sensory systems: visual, somatosensory, vestibular.

The visual, somatosensory, and vestibular systems have often been studied with respect to their roles in the control of posture. These redundant inputs code information pertaining to the relationship between the body with itself and the environment, where each sensory modality operates within a specific range of frequency and amplitude of sway (Johansson & Magnusson, 1991). While each input conveys specific types of information, the fusion between the sensory systems creates a redundancy that allows for the clarification of ambiguous signals (Jeka et al., 2000). For example, an image moving across the retina can either be perceived as self-motion or motion of the environment. This ambiguity could be solved by using information from the vestibular system responding to a linear acceleration of the head, indicating self-motion rather than motion of the visual environment. This process describes a sensory re-weighting process, where the postural control system dynamically re-weights multiple sensory inputs to maintain upright stance as the sensory environment changes (Peterka, 2002). This process along with the redundant nature of the three inputs allows for the elucidation of an ambiguous piece of sensory information.

In certain situations the redundancy in the information given by the sensory systems also allows for the maintenance of stance even when one modality is distorted or taken away. It is this relationship between the manipulated or removed sensory information and the postural response that allows for the behavior of posture to be used as a model for the use of sensory information, where the effect of varying sensory input on postural sway may lead to a better understanding of the role sensory information plays in postural control. One method used to characterize the use of vision in the control of posture has been to observe quiet standing with and without vision.

The Influence of Vision on Posture

Eyes open vs. Eyes closed

In adults, when quiet stance is compared with and without vision, quiet stance with eyes closed is slightly destabilized relative to quiet stance with eyes open (Riley, Wong, Mitra, & Turvey, 1997; Riley & Turvey, 2002; Ashmead & McCarty, 1991). Although this result is widely found in the adults, the findings in children and infants are conflicting. Ashmead & McCarty (1991) have found that infants generally did not sway more in the dark than in the light, illustrating possible developmental differences in the use of vision for postural control. However, the children's literature on this issue is characterized with inconsistent results, making it difficult to come to a strong conclusion on vision's role in quiet stance control. Where some have reported a stabilizing effect of vision on children's quiet stance (Riach & Starkes, 1989; Riach & Starkes, 1994), others have reported that vision does not have the same stabilizing effect as in adults (Riach & Hayes, 1987; Portfors-Yeomans & Riach, 1995). These conflicting findings have resulted in no definitive characterizations of the effect of eye closure on quiet stance sway in children and may be an indicator of a variable relationship between vision and postural control in children. An alternative explanation may come from the differing visual stimuli used across these studies. Visual influences on sway are known to depend on visual stimulus quality, for example, decreases in the size of a fixation point have been shown to increase sway (Paulus, Straube, & Brandt, 1984). It is possible that the variability found in these studies may be due to the differences in the stimulus quality across studies. Further research needs to be done with a standardized visual stimulus to determine whether these results indicate a difference between children and adults in their use of vision for postural control, or if these results reflect the differences in the visual stimulus presented.

While the eyes open vs. eyes closed comparison can give us some insight into the development of vision's influence on sway, such large changes in sensory function should be considered a small part of the description (Oie et al., 2002). Individuals are more likely to encounter dynamic sensory changes in the environment rather than abrupt removal of sensory information. One method used to observe the effect of dynamic changes in the visual environment on postural sway is to vary the visual environment in an experimental paradigm that has been called the "moving room".

Dynamic Visual Stimulus

In the moving room paradigm, a participant stands on a stationary floor where the visual environment translates with respect to the stationary floor either by physically moving the walls and ceiling, or by the movement of a computer generated image relative to the stationary floor. Movement of the visual environment has been shown to elicit postural responses from the participant standing within the moving room (Stoffregen, 1985; Berthoz, Lacour, Soechting, & Vidal, 1979; Lishman et al., 1973; Stoffregen, 1985; Guerraz, Gianna, Burchill, Gresty, & Bronstein, 2001). As the visual environment is translated toward the participant, the visual flow information presented is one that suggests forward sway eliciting compensatory sway in the direction of the translation movement. When the visual environment is oscillating at low frequencies, the participant's postural sway adopts the frequency of the oscillation of the visual environment, where this coupling response is dependent upon the spatio-temporal aspects of the visual stimulus (Lestienne, Soechting, & Berthoz, 1977; Masson, Mestre, &

Pailhous, 1995; Jeka et al., 2000). The moving room allows the exploration of the relationship between vision and posture and differences in this relationship developmentally could be characterized by differences in the postural response to the moving room.

Lee and Aronson (1974) were the first to observe the infant's postural response to the moving room. Infants 13-16 months of age, who where just beginning to stand, were placed in the moving room and found to respond by swaying or sometimes falling in the direction of the room movement, showing a directionally appropriate response (Lee & Aronson, 1974). These findings were extended to infants who can sit but not yet stand, where the results showed the younger age group would lean in the appropriate direction while seated within the moving room (Butterworth et al., 1977). This suggests that visual perception of self-motion is present before upright locomotor experience, where these improvements have been shown with experience (Anderson et al., 2001). Bertenthal and Bai (1989) replicated these findings by observing 5-, 7-, and 9-month-olds supported on a bicycle seat with measurements of forces taken under the seat. The results showed the 7- and 9-month-olds showed directionally appropriate sway, while the 5-month-olds did not. One interpretation may be that 5-month-olds could not utilize optic flow information and therefore did not show a sway response, or the infants did perceive the optic flow, but lacked the muscle strength and coordination to control a postural response(Bertenthal & Bai, 1989). To further investigate this issue, further studies where done and found that younger infants and even neonates showed directionally appropriate responses within the moving room (Jouen, 1984; Jouen, 1988; Jouen, Lepecq, Gapenne, & Bertenthal, 2000).

Taken together, these studies suggest that infants younger than 5 months, while lacking the muscle strength and coordination to control posture, are able to perceive optic flow as information pertaining to self-motion. While these results are compelling, it should be noted that many of these studies utilize room movements of large amplitude (<10 cm), distances that when compared to the mechanics of the infant may be seen as a visual perturbation, where these results may be interpreted as compensations to abrupt sensory changes rather than a coupled visuomotor response. Therefore, a full characterization of the response to a dynamic visual stimulus would require the inclusion of small amplitude stimuli.

Schmuckler (1997) looked to characterize the postural response of 3 to 6-yr-old children to a moving room at varying speeds of motion to investigate the developmental changes in the use of visual information for the control of posture in children. The author presents a hypothesis where frequency, amplitude and timing may be parameters that are each associated with different developmental trajectories. Results showed that children responded to oscillating visual information ranging from 0.2 – 0.8 Hz, and that the frequency, amplitude and timing parameters of the postural response to the visual stimulus revealed a mixture of adultlike and nonadultlike control. Again, these results are limited as the visual stimuli presented to the participants contained large amplitudes. If the postural response in children depends upon the spatio-temporal aspects of the stimulus, as they do in adults, we may observe different results with smaller stimulus amplitudes. Furthermore the results showed with respect to the timing parameter, that as the frequency of the stimulus increased, the time lag between the visual stimulus and the postural response increased, as in adults (Dijkstra et al. 1994; Jeka et al, 2000). With respect to the amplitude of the children's response, it was found that as the frequency increased, the mean sway amplitude increased. The authors conclude that the children responded to the entire stimulus frequencies presented, but the amount of response at each frequency, with respect to the visual stimulus, is in question, as it was not directly measured. One way the amount of response to the visual stimulus could be characterized is with the measure of gain. If the postural response to the visual stimulus is composed of adult-like and non-adultlike control as the author suggests, linear systems analysis may reveal differences in the gain and phase responses between the children and adults, characterizing the developmental trajectories of the amplitude and timing of the response.

The Development of Posture: The Effects of Tuning to Visual Information

Taken together, these findings suggest that the development of the postural response to a dynamic visual stimulus lies within the ability to scale or "map" the sensory information to the motor response (Bertenthal et al., 1997; Bertenthal & von Hofsten, 1998). Improvements in the "mapping" of the sensory input to motor action are demonstrated with increased spatial and temporal precision of the postural response to the dynamic stimulus, consistent with the notion of a response "tuning". Tuning in this context is representative of an increase in the coordination between the sensory input and the motor response. One way to quantify this tuning response across age would be to observe a decrease in the variability of the postural response to the moving room. This decrease in the variability would be associated with increased precision in the amplitude and timing of the response along with a reduction of sway not associated with the movement of the stimulus. Bertenthal et al. (1997) observed 5, 7, 9, and 13 month olds while seated within a moving room and found that the infants scaled their postural sway to the frequency and amplitude manipulations of the visual stimulus, where this entrainment to the stimulus showed an age-related improvement with sitting experience. The timing of the response also improved with age as indicated by a decrease in the time lag between the postural sway and the movement of the room. These findings illustrate an increased precision of responding to the visual stimulus with development that could be characterized as postural response tuning. It is important to again note that these are findings from an experiment that utilized large amplitude visual stimuli that may be seen as a perturbation to the infant participants and may not represent the small sensory changes seen in everyday interaction with the environment. Nevertheless, this tuning conceptualization is useful for the understanding of postural control development and will require further study with small amplitude stimuli to extend the previous work.

What is the underlying changes occurring in the postural control system that results in these tuning effects in postural sway with age? Some insight into this question may come from a closed-loop feedback control model of upright stance. Peterka (2000) utilizes a model consisting of a body represented by an inverted pendulum with torques applied to the ankles to describe sway trajectories. This model detects an error signal (desired vs. actual postural state) generated by information from the sensory inputs to create these corrective torques. These compensatory movements are scaled based upon position and velocity information received from the sensory inputs. A simulation of this model with varying weights for the position and velocity parameters produced a number of sway profiles, some that resemble adult sway (Peterka, 2000). However, it also produced sway profiles with large amounts of variability, similar to children's sway. Based upon this simulation, one hypothesis is that the process of postural response tuning may lie within the selection of optimal tuning of the sensory weights with age. This tuning process must also take into account the changes in the mechanical system from infancy to adulthood (McCollum & Leen, 1989). This would be represented as changing parameters of the inverted pendulum in the feedback control model, requiring changes in the sensory weights as they need to be based upon the most current properties of the mechanical system. Therefore, changes in the mechanics must be accounted for in the selection of the sensory weights to produce stable postural control.

Jeka et al. (2000) characterizes the adult postural response to an oscillating visual stimulus by examining the effect of varying spatio-temporal parameters of the visual stimulus on the postural response. Linear systems analysis is used to quantify the response to the visual stimulus in the frequency domain, where measures of gain and phase are calculated. Gain is defined as the amplitude of the postural response, at the stimulus frequency, divided by the stimulus amplitude at that frequency. If the postural sway component at the stimulus frequency is similar in amplitude to that of the visual stimulus, the gain values should be close to one. Phase can be described as a normalized representation of the time delay between the stimulus and the postural sway, where a phase lead suggests body sway that is ahead of the stimulus, while a phase lag represents body sway behind the stimulus. When a visual stimulus is presented with parameters that are close to the natural frequency of sway in adults, an in-phase relationship is shown with gain responses close to one (Dijkstra, Schöner, Giese, & Gielen, 1994; Dijkstra, Schöner, & Gielen, 1994). When a visual stimulus is presented at a frequency below 0.2Hz, a decreased gain response is shown, with a phase lead relationship. When a visual stimulus is presented with a frequency above 0.2Hz, a decreased gain relationship is shown with a phase lag. These differing responses to varying stimulus parameters illustrate the dependency of the postural response on the spatio-temporal aspects of the visual stimulus.

Peterka & Benolken (1995) also have shown this dependence with changes in the postural responses to varying amplitudes of visual stimuli, where stimulus frequency was kept constant. Results showed a saturation effect where past a threshold level, the increase in visual stimulus amplitude did not evoke increases in sway amplitude. This saturation level was also found to be dependent upon the frequency of stimulus oscillation. Furthermore, in a comparison between normal participants and bilateral vestibular patients it was found that normals showed a saturation effect while the vestibular patients did not (Peterka & Benolken, 1995). In other words, for vestibular patients increases in visual stimulus amplitude elicited increases in sway until falling. This implies that the sensory cues that create this saturation phenomenon are of vestibular origin. Furthermore, the sway response of both the normal and vestibular patients were similar until the saturation point was reached, suggesting a threshold where the reliance on visual inputs are downgraded and veridical vestibular inputs are utilized.

This saturation phenomenon suggests a sensory re-weighting process, where the postural control system dynamically re-weights multiple sensory inputs to maintain upright stance as sensory conditions change (Forssberg & Nashner, 1982; Oie, Kiemel, & Jeka, 2002). Sometimes these changes in sensory conditions can cause ambiguity that the control system must resolve using this sensory re-weighting process. In other words, flexible balance control requires an increase in weights to some inputs and a decrease in weights to others (Horak & McPherson, 1996). Results from Peterka & Benolken (1995) may indicate that the control system sees large amplitude movements as non-veridical and downplays visual information, causing the saturation of the response. This view assumes a categorization scheme used by the control system where small amplitude stimuli indicates self-motion and large amplitude motion indicates object motion (Schöner et al., 1998). Categorization of inputs as object motion rather than self-motion would result in setting that weight low or to zero, a process that helps maintain balance in a dynamic sensory environment.

Summary

The use of visual information as an indicator of self-motion seems to be present early in life, even before postural abilities are attained. When postural milestones are achieved, the influence of vision is seen in sway responses to dynamic visual environments. This relationship between vision and posture is said to show improvement within the first years of life, marked by an increased precision to the dynamic stimulus, or a tuning of the postural response (Bertenthal et al., 1997). However, previous studies in infants and children have utilized large amplitude movements, akin to a visual perturbation rather than a demonstration of continuous visuomotor control. Furthermore, the adult's response has been shown to depend upon visual stimulus amplitude, where a saturation point is seen at a threshold amplitude level. Therefore, further characterization of the tuning response will require examination of the postural response to small amplitude stimuli to extend previous findings.

CHAPTER III

AGE-RELATED CHANGES IN THE USE OF VISION FOR POSTURAL CONTROL: THE EFFECTS OF VARYING FREQUENCY

Introduction

Stable perception-action relationships are required so that our movements can adapt to the changing demands of the environment. It has been thought that these relationships exist from the beginning of life, and at no point in development are they uncoupled (Thelen, 2000). However, researchers have hypothesized that one of the underlying factors in the development of motor skills is an improvement in the coordination between perception and action (Bertenthal, Boker, & Xu, 2000; Bertenthal et al., 1997). In other words, the development of skilled actions can be conceptualized, in part, as a stabilization of the perception-action relationship. Based on this hypothesis, an understanding of the relationship between sensory information and motor action is important to our understanding of motor skill development.

There are many approaches to study the development of perception-action relations. A paradigm, referred to as the “moving room” paradigm, has been used to study the postural response to changing visual stimuli. In this paradigm, the participant stands on a stationary floor surrounded by a moving visual environment created by either a computer generated image or by physically moving the walls and ceiling relative to the stationary floor. A discrete linear movement of the visual environment toward an adult participant creates visual flow information that suggests forward sway, eliciting compensatory sway in the direction of the movement of the room, with a more exaggerated sway response in young children (Lishman & Lee, 1974).

Jeka et al. (2000) characterized the adult postural response to an oscillatory visual stimulus and found that adults will consistently entrain their sway with the motion of the stimulus. In other words, a stabilized or coordinated perception-action system (i.e., adult) will respond with a distinct and consistent sway response that corresponds with the amplitude and frequency of stimulus oscillation. The postural response also was found to adopt a particular temporal relationship with the stimulus such that sway leads the stimulus at lower frequencies (<~0.25Hz) and lags behind the stimulus at faster frequency oscillations (>~0.3Hz).

To examine the effect of a dynamic visual stimulus on the postural response as it occurs early in development, Bertenthal et al. (1997) observed 5-, 7-, 9-, and 13-month-olds while seated within a moving room. The authors found that the infants scaled their postural sway to the frequency and amplitude manipulations of the visual environment and that this entrainment to the stimulus showed an age-related improvement with sitting experience. The timing of the response also improved with age as indicated by a decrease in the time lag between the postural sway and the movement of the room. Since the infants showed this scaling response before they could sit unsupported, the authors concluded that the visual control of sitting is not rate-limited by the perception of the visual stimulus. This suggests that the development of the postural response to a dynamic visual stimulus lies within the infant's ability to scale or "map" the sensory information to the motor response. Improvements in the "mapping" of the sensory input to motor action is demonstrated with increased spatial and temporal precision of the postural response to the dynamic stimulus, consistent with the notion of a response "tuning". Tuning in this context is representative of an increase in the coordination between the sensory input and the motor response. One way to quantify this tuning response across age would be to observe a decrease in the variability of the postural response to the moving room. This decrease in the variability would be associated with increased precision in the amplitude and timing of the response along with a reduction of sway not associated with the movement of the stimulus.

The changes in the tuning of the postural response to a dynamic visual stimulus between children and adults may also indicate age-related differences in the use of vision for the control of posture. Schumway-Cook and Woollacott (1985) suggested a transition period between 4 to 6 years of age in the use of sensory information for the control of posture. According to the authors, vision is the primary source of information used to control posture early in the transition period. By the end of this period, the child is able to integrate inputs from the visual, somatosensory and vestibular systems in an adult-like manner. If this age range truly represents a transition period, then the 4-year-olds postural response will demonstrate dependence on the visual stimuli showing clear age-related differences when compared to 6-year-olds and adults. In other words, this transition period would represent a change in the use of sensory information for postural control. This change in the nature of the perception-action relationship will lead to changes in tuning of the postural response. This hypothesized transition period also suggests that children 6 years and older should show an adult-like tuning of the postural response.

To investigate this hypothetical transition period in the use of sensory information for children's postural control, Schmuckler (1997) looked to characterize the postural response of 3- to 6-yr-old children to a moving room and found that children in this age range responded to oscillating visual information ranging from 0.2 – 0.8 Hz, where the frequency response appeared non-adultlike, and the timing measures revealed an adult-like response. From these results, the authors concluded that the children's response to the visual stimulus revealed a mixture of adultlike and nonadultlike control (Schmuckler, 1997). These results are difficult to interpret, however, because of the large visual stimulus amplitudes (10-12cm) presented to the participants. Large amplitude visual stimuli may act as a sensory perturbation to the child, where the postural response would reflect compensatory control as opposed to continuous sensory motor coupling.

The purpose of the present study, therefore, is to examine the postural response to a dynamic visual stimulus in children by characterizing the amplitude and timing responses to varying frequencies of oscillation where the stimulus amplitudes are much smaller than those used by previous investigators. If a tuning response occurs across age it will be characterized by increased precision in the amplitude and timing parameters of posture at the driving frequency, with decreased sway not associated with the visual stimulus. Furthermore, a comparison of the postural response to varying frequency conditions across age 4-6 will test for the possible existence of a transition in the use of vision for the control of posture during this age period. If this transition does exist then the 4-year-old's postural response should be different from the 6-year-olds and adults.

Method

Participants

Participants in the study where seven 4-year-old children (M = 4.43, SD = 0.35 years) and seven 6-year-old children (M = 6.4, SD = 0.7 years) and seven adults (M = 23.2, SD = 2.6 years) All children were healthy, normally developing. All participants had normal or corrected vision. Participants where recruited from an area in and surrounding the University of Maryland, College Park. Each child's parent or guardian and adult participants gave written informed consent prior to participation according to procedures approved by the Institutional Review Board at the University of Maryland at College Park (see appendix A for a copy of the consent form).

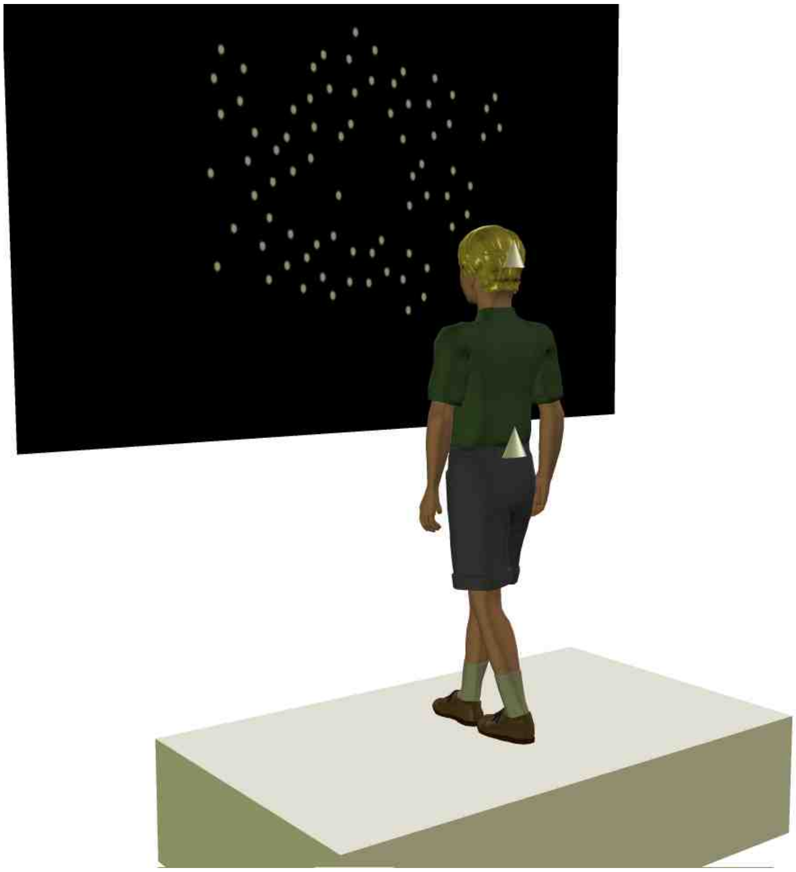

Figure 1. Illustration of the Experimental Setup

Experimental Set-Up

Figure 1 illustrates the simulated moving room, where the visual stimulus consisted of an image of randomly scattered small white triangles on a black background (0.2 degrees X 0.2 degrees) that was back-projected onto a translucent screen (2.5m x

1.0m) from a mounted projector (Electrohome™). All points in the visual array moved synchronously in the medio-lateral (ML) direction at the same velocity creating simple horizontal flow at frequencies of 0.1, 0.3, and 0.5 Hz (i.e., stimulus conditions) with amplitudes of 1.5, 0.6, and 0.3 cm respectively and a constant velocity of 0.65 cm/s.

To measure the mediolateral postural response to the visual stimulus, an ultrasound tracking system (Logitech, Inc.™) was used to measure 3D-body sway. The system consisted of a control unit, a triangular ultrasonic transmitter (25x25x25cm) and two small triangular ultrasonic receivers (7x7x7cm). The participants wore a headband on which one of the ultrasonic receivers was attached to measure the displacement of the head, and the second receiver was affixed to the participant's waistband to measure the displacement at the approximate center of mass. The ultrasonic transmitter was mounted on a tripod positioned approximately one meter behind the participant during the experimental session. All signals from the tracking system and the visual stimulus were collected at 50.33 Hz via a National Instruments A/D board (SB-MI06) on a PC (Gateway G6-200) workstation using a custom LabView data acquisition program.

Procedure

Once acclimated to the laboratory environment, the participants where asked to stand quietly in a modified tandem stance (toe touching medial side of heel) 40cm from the screen where the stimulus conditions (i.e., frequencies) were presented in a random fashion. The participants wore goggles to limit the field of view approximately 100 degrees high by 120 degrees wide, so that the edges of the screen were not visible. At the beginning of a trial, the stimulus appeared along with a small image of a clock. The clock then disappeared at the start of the trial when the stimulus began oscillating. When the trial was over, the clock reappeared and disappeared again when the next trial started. The participant was asked to attend to the screen and report when the clock disappeared and reappeared, in effect keeping the child on task. The total experimental session consisted of three trials of each condition presented in random order, for a total of nine trials, each lasting 60-90 seconds depending upon the condition (to be able to include the same amount of cycles), for a total of approximately 1.5 hrs, including breaks when the participant received prize incentives. All trials where videotaped to ensure that the participants adhered to the task constraints during the entire session.

Analysis

Measures

Using a linear systems analysis in the frequency domain, three measures were used to examine the position data collected from the head and approximate center of mass (CoM): gain, phase and residsway. Fourier transforms of the postural displacements and the stimulus position were computed, where the transform of the postural displacements at the driving frequency was divided by the transform of the stimulus position, also at the driving frequency, creating the transfer function or the frequency-response function from where the measures of gain and phase where recovered.

Gain is defined as the ratio between the body sway amplitude spectrum and the visual stimulus amplitude spectrum at the driving frequency. Gain values of close to 1 represent body sway amplitude that is similar to the visual stimulus amplitude at the driving frequency. Values lower than 1 represents body sway amplitude that is less than the visual stimulus amplitude, and values greater than 1 represent body sway amplitude that is greater than the visual stimulus amplitude. Gain represents the strength of the postural response relative to the stimulus and comes from the absolute value of the transfer function. If a transition period exists in the use of sensory information for postural control between 4 and 6 years of age from visual dominance to the integration of sensory inputs, changes in the gain response will be evident. Based on this hypothesis, 4-year-olds (visually dominant) will show a constant gain across frequency. This would represent a linear amplitude response with respect to changes in the amplitude properties of the stimulus. In other words, if the 4-year-old is truly visually dominant, the sway response will be strongly influenced by the driving visual stimulus no matter what parameters are set as we expect changes in the amplitude of the stimulus to be reflected in the sway response amplitude at a constant ratio. Furthermore, the 6-year-olds (multisensory capable) will show a gain response that is dependent upon stimulus frequency based upon previous work with adults (Jeka et al., 2000). This response will be an indication that the 6-year-old's response will not be visually dominant, but based upon the spatio-temporal structure of the stimulus. If response tuning occurs with development, we expect a decrease in gain variability with age, suggesting an increased precision of the amplitude response.

Phase is the normalized representation of the delay between the body sway and the visual stimulus, recovered as the complex value of the transfer function. A phase value of zero represents no time delay between the response and the stimulus. Phase values greater than zero represents body sway leading the stimulus, while negative phase values represent body sway lagging behind the stimulus. We expect the 4-year-olds, based upon the hypothesized transition period, to show a constant phase response across stimulus frequency. This will demonstrate the visual dominance hypothesized where the timing relationship will be determined by the frequency of the stimulus, where changes in this stimulus parameter will show proportional changes in the sway response timing. The 6-year-old's timing response will be similar to the adult's response. Previous work in adults (Dijkstra et al., 1994) shows a timing response where we would expect a phase lead relationship at the 0.1 Hz condition, with increasing phase lags at the 0.3 and 0.5 Hz conditions. If a tuning response occurs with development, an increased precision of the timing response will be shown with decreased phase variability across age.

The residsway is defined as the standard deviation of the residual sway contained in the frequencies above and below the stimulus frequency and represents the sway that does not contribute to the amplitude and timing measures (gain and phase). The residsway was estimated by first detrending the postural sway trajectory. The postural sway component due to the visual stimulus was removed by subtracting the sinusoid corresponding to the Fourier transform of the trajectory at the visual stimulus frequency. The residsway is the standard deviation of the resultant trajectory. If a tuning response exists with development, the residsway is expected to decrease with increasing age, indicating an increased precision in the postural response with development.

Statistical Analysis

Utilizing a mixed model (Proc Mixed, SAS, version 8.2), six separate 3x3 ANOVAs (age and frequency) for the head and center of mass for each measure, with repeated measures on frequency were utilized to evaluate the effects of age (4, 6 and adult) and the three visual stimuli frequencies (0.1, 0.3, 0.5Hz). The dependent measures where gain, phase and residsway. Significant effects were followed by LSD post-hoc procedures.

Results

The results are divided into two sections. The first section characterizes the postural response amplitude and timing with the measures of gain and phase respectively. The second section describes the amplitude and timing variability, along with the amount of sway not associated with the stimulus frequency, to analyze the postural response tuning. This section includes the standard deviations of the gain and phase with the measure of residsway.

Stimulus Response

Amplitude

Repeated measures ANOVA for head gain (Figure 2) revealed a significant main effect for age ($F(2,36)=3.62$, $p<0.05$) and condition ($F(2,12)=14.87$, $p<0.05$), but revealed no interaction. Post-hoc analysis of the condition effect revealed all groups' responses at the 0.1 Hz condition were significantly lower than their responses at 0.3 and 0.5 Hz stimuli. For the age main effect, the 4-year-olds had higher gain values across conditions than the adults, but were not different from the 6-year-olds who did not differ from the adults.

Repeated measures ANOVA for CoM gain (Figure 3) also revealed a significant main effect for age ($F(2,36)=9.97$, $p<0.001$) and condition ($F(2,12)=7.47$, $p<0.001$), and no interaction. As with the head response, the condition effect for CoM revealed gain at the 0.1 Hz condition to be significantly lower than the other frequencies which did not differ from each other. CoM gain for both the 4- and 6-year-olds were greater than the gain seen in adults, but did not differ from each other.

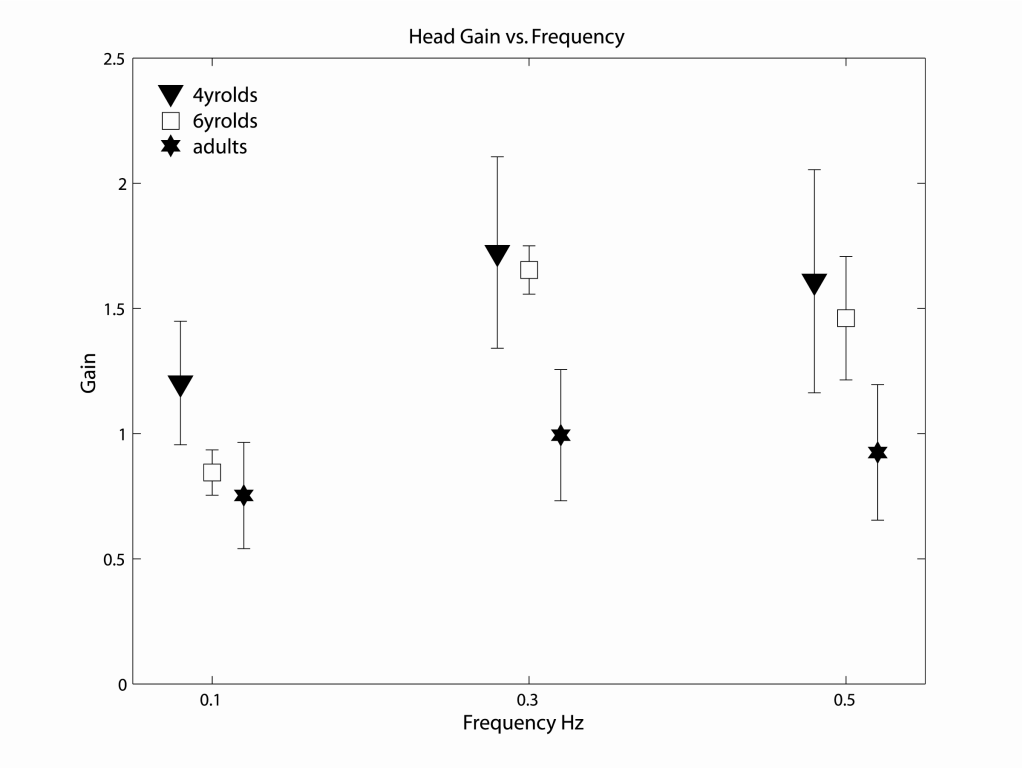

Figure 2. Mean Gain Values and the Standard Error of the Mean for the Head Across Frequency

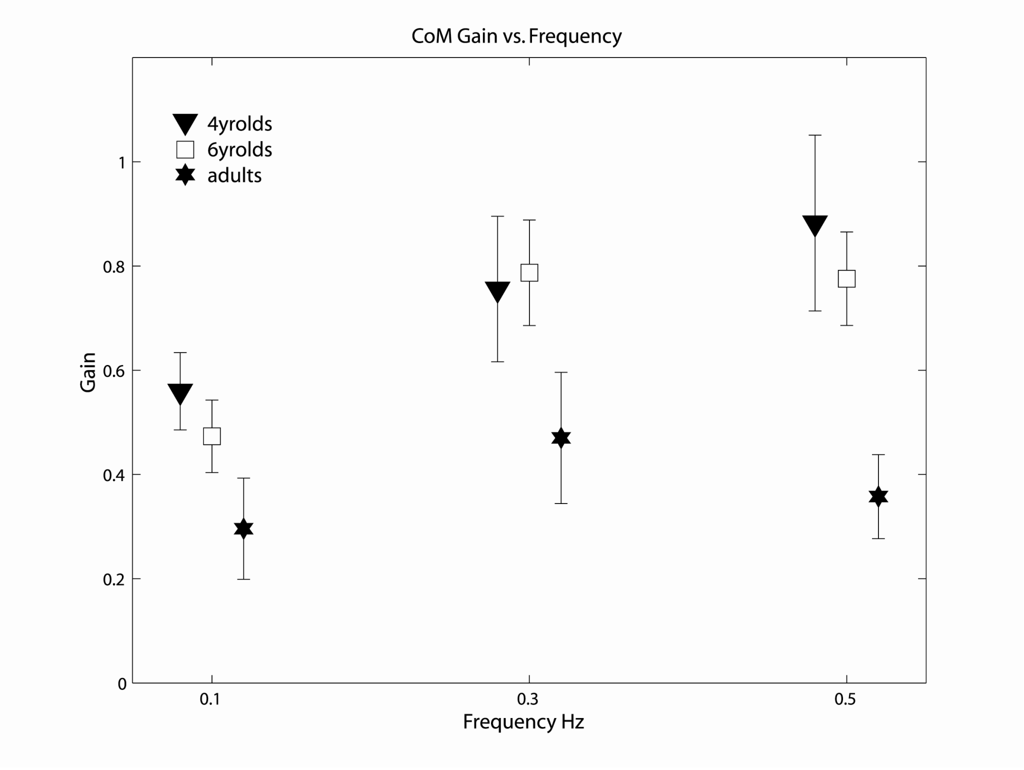

Figure 3. Mean Gain Values and the Standard Error of the Mean for the Head Across Frequency

Timing

To assess the temporal structure of the response relative to the stimulus, repeated measures ANOVA for the head's phase (Figure 4) revealed a condition effect ($F(2,18)=36.06$, $p<0.05$) with no age effect or interaction. Post-hoc analysis of the condition effect revealed significant differences across all 3 conditions, with the largest phase values at the 0.1 Hz condition, followed by the 0.3 Hz condition, with the lowest gain values at the 0.5 Hz condition.

Repeated measures ANOVA for the CoM phase (Figure 5) revealed a condition effect ($F(2,18)=9.94$, $p<0.05$) with no age effects or interaction. Post-hoc analysis of the condition effect revealed positive phase values at the 0.1 Hz condition indicating a phase lead response with negative phase responses at the 0.3 and 0.5 Hz conditions which did not differ from each other, indicating a phase lag.

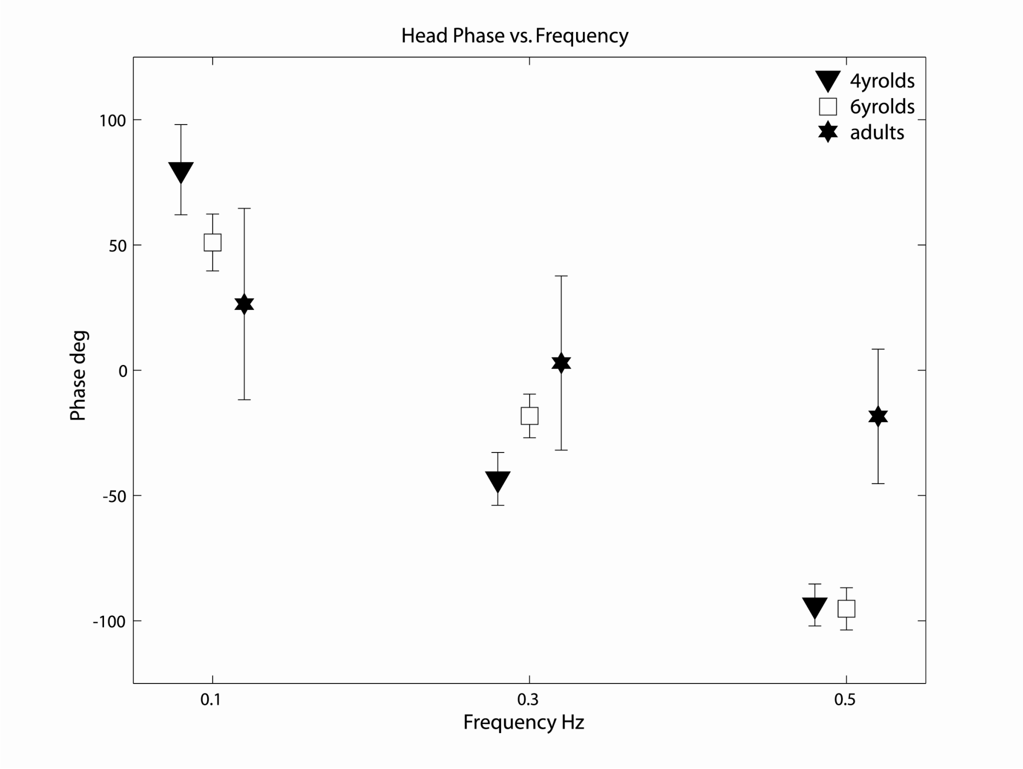

Figure 4. Mean Phase Values and the Standard Error of the Mean for the Head Across Frequency

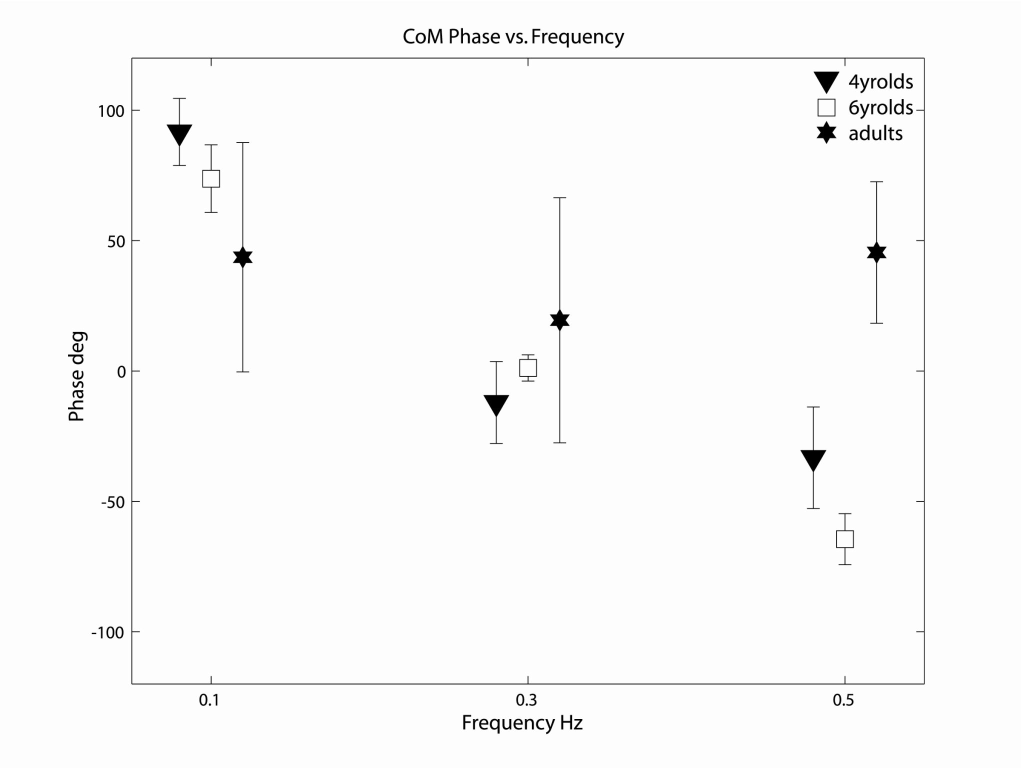

Figure 5. Mean Phase Values and the Standard Error of the Mean for the CoM Across Frequency

Variability of the Response

Amplitude variability

The stability of the amplitude response was measured as the standard deviation of the mean gain values. Repeated measures ANOVA for the head variability (Figure 6) revealed age effects ($F(2,36)=4.85$, $p<0.05$) and condition effects ($F(2,12)=4.49$, $p<0.05$) but revealed no interaction. Post-hoc analysis of the condition effect showed the largest variability at the 0.3 Hz condition with similar responses at the 0.1 and 0.5 Hz conditions. The age effect showed the 4-year-olds where more variable than the adults, while the comparison between the 6-year-olds and the adults approached significance (p = 0.052).

Repeated measures ANOVA for the variability of CoM (Figure 7) revealed an age effect (*F*(2,36)=6.14, *p*<0.05) with no condition effect and no interaction. Post-hoc analysis of the age effect revealed the 4- and 6-year-olds were similar and had higher variability than the adults.

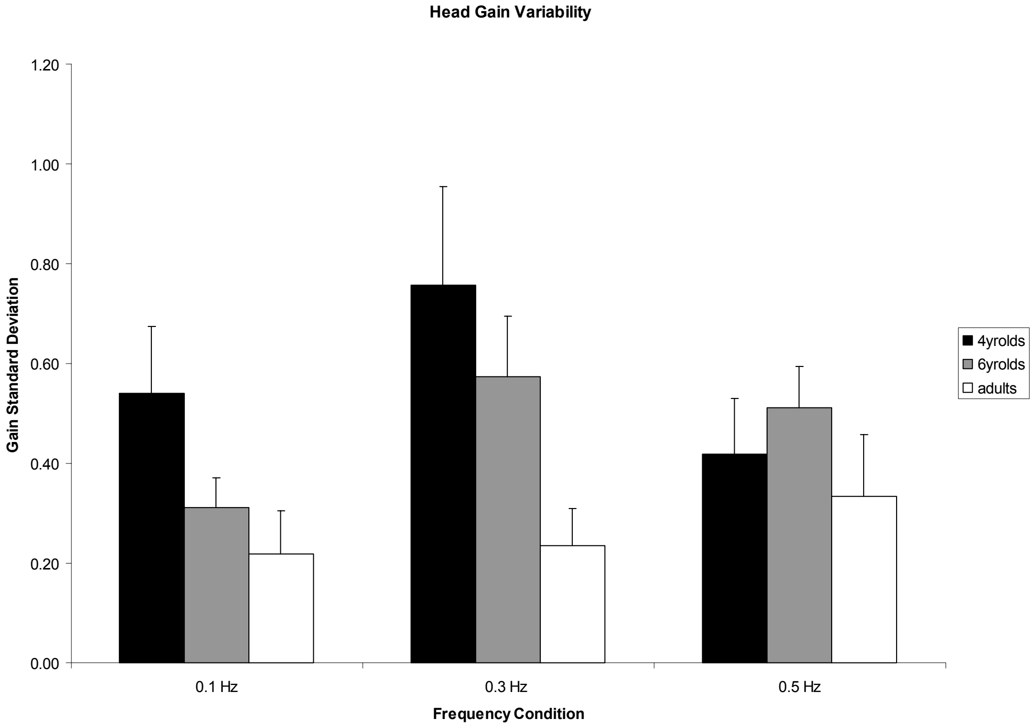

Figure 6. Standard Deviation of the Head Gain Across Frequency

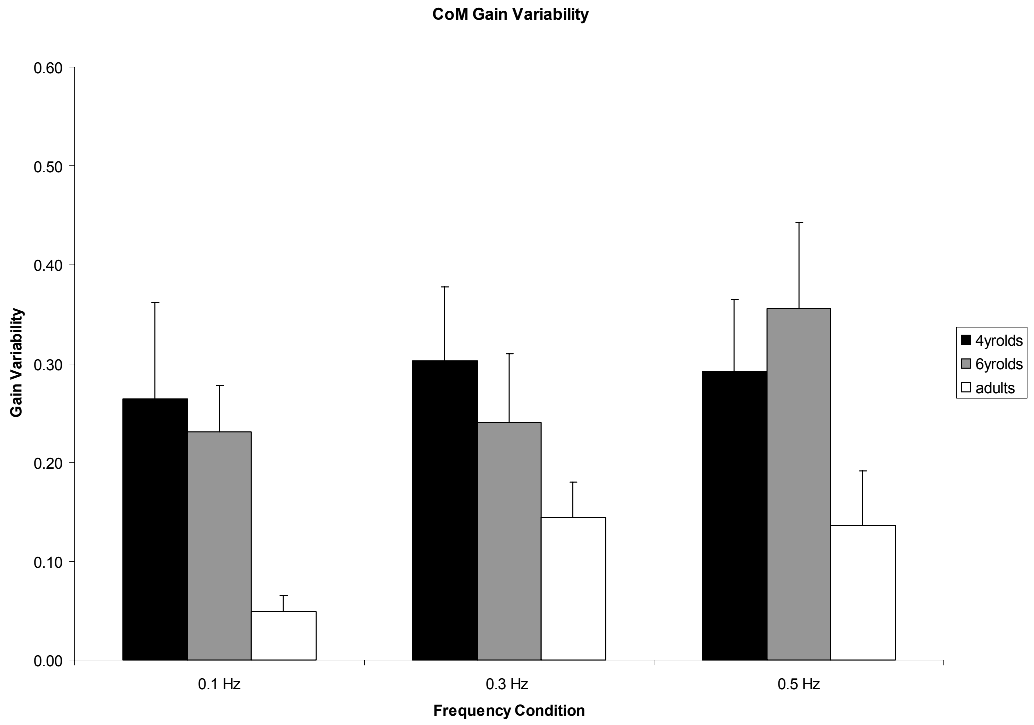

Figure 7. Standard Deviation of the CoM Gain Across Frequency

Timing variability

Phase variability (Figure 8) was assessed to describe the stability of the timing response to the driving stimulus. Repeated measures ANOVA for the head revealed no significant main effects. A similar result was found for the CoM (Figure 9).

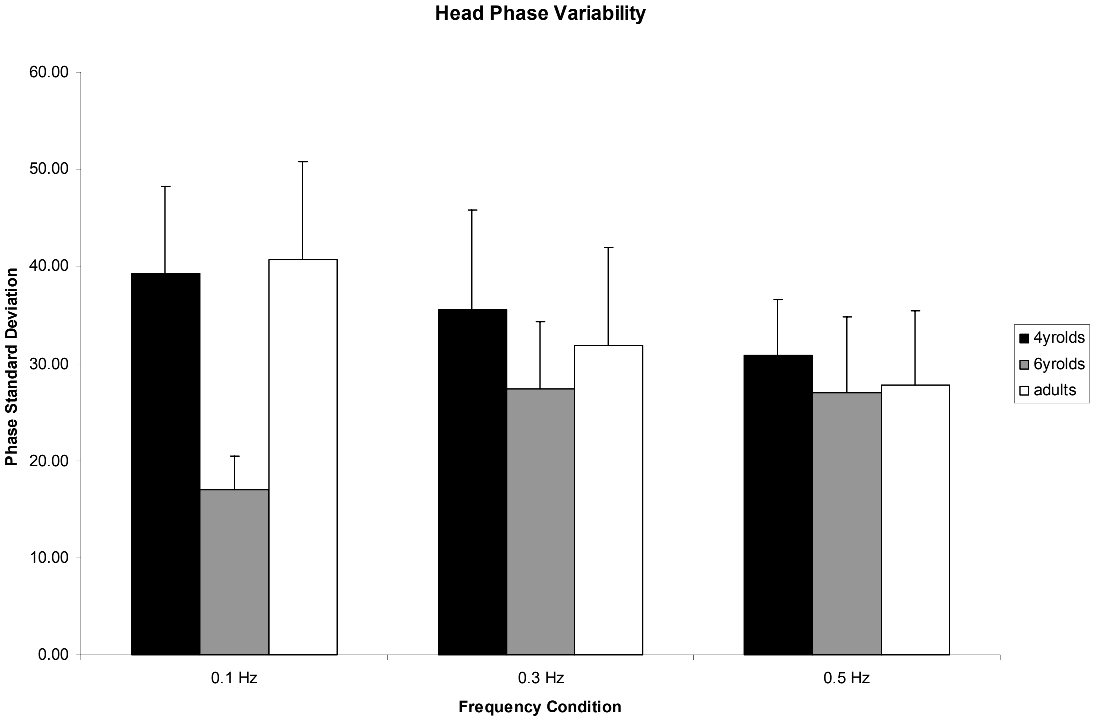

Figure 9. Standard Deviation of the Head Phase Across Frequency

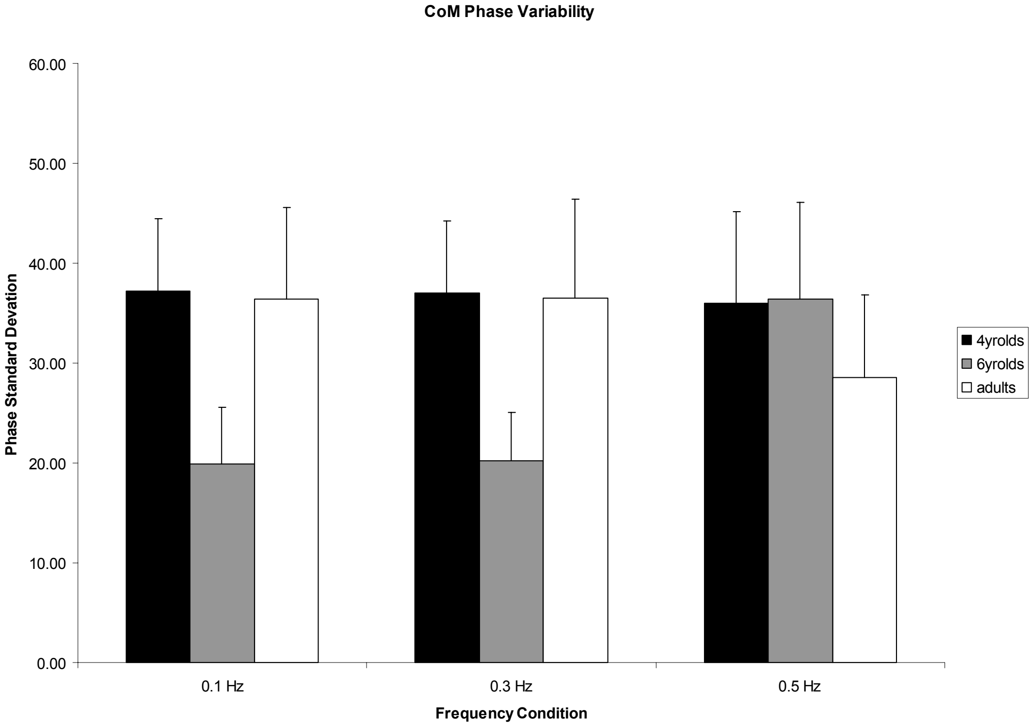

Figure 8. Standard Deviation of the CoM Phase Across Frequency

Sway variability

Repeated measures ANOVA for the residsway for the head (Figure 10) revealed an age effect (*F*(2,36)=25.76, *p*<0.05) and condition effect (*F*(2,12)=20.44, *p*<0.05) but showed no interaction. Post-hoc analysis of the condition effect found the lowest residsway response at the 0.1 Hz condition which was significantly different from the other two frequencies which did not differ from each other. Post-hoc analysis of the age effect revealed the 4-year-olds had the greatest residsway response, followed by the 6-year-olds, where the adults showed the lowest residsway response.

Repeated measures ANOVA for the residsway of the CoM (Figure 11) revealed an age effect (*F*(2,36)=26.48, *p*<0.05) along with a condition effect (*F*(2,12)=11.89, *p*<0.05) and no interaction. As seen in the head, condition effect showed the lowest residsway response at the 0.1 Hz condition, while the age effect revealed a decrease in residsway across age as each age group was significantly different from each other.

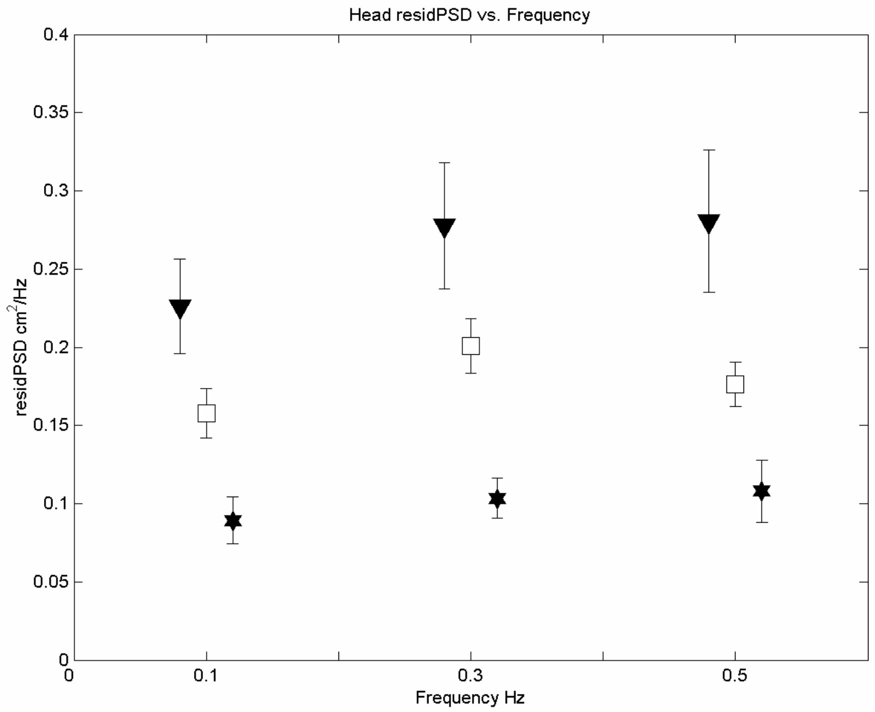

Figure 10. Mean residsway Values and the Standard Error of the Mean for the Head Across Frequency

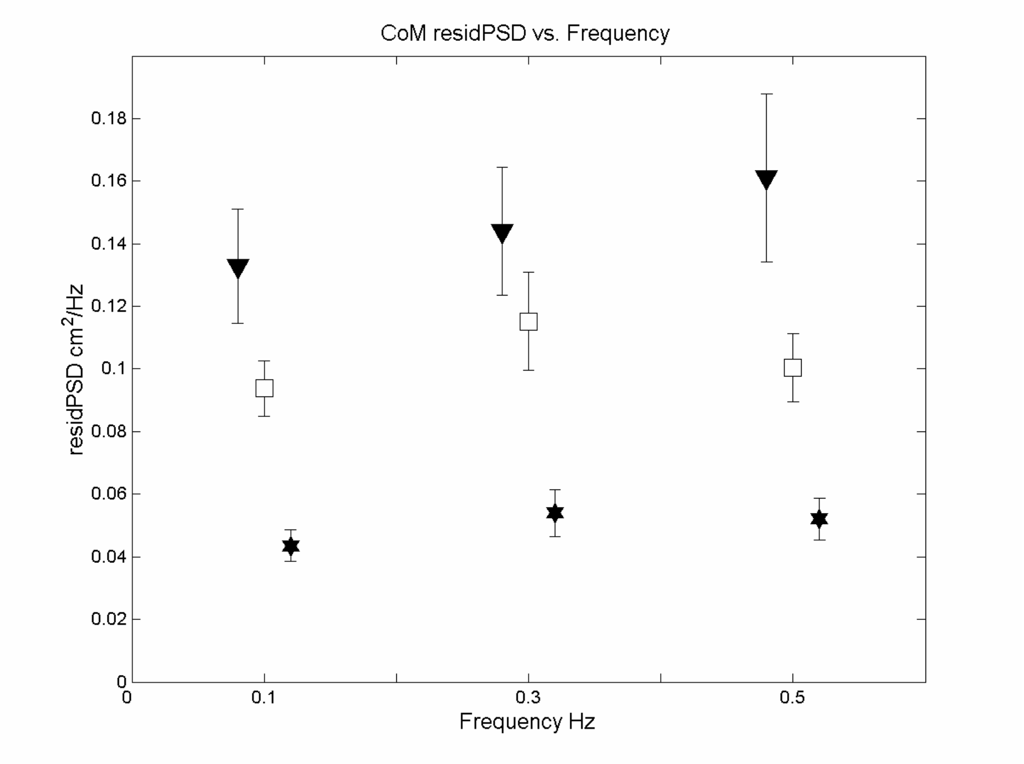

Figure 11. Mean residsway Values and the Standard Error or the Mean for the CoM Across Frequency

Discussion

The goal of the present study was to characterize the effect of varying visual stimulus frequency on the postural response in children. For all participants, results showed the amplitude gain to be the lowest at the 0.1 Hz condition, with larger gain responses at the 0.3 and the 0.5 Hz condition. Gain values indicate that the response from the head at the 0.1 Hz condition approached unity, where the amplitude of the response closely matched the stimulus amplitude, while the response at the 0.3 and 0.5 Hz conditions showed larger gain representing an amplitude response greater than the stimulus. The gain response pattern across frequency was shown to be the same for all age groups, where the developmental differences were seen in the decreased gain magnitude with age. With respect to the response timing, a phase lead was found at the

0.1 Hz condition, indicating that the response was temporally ahead of the visual stimulus. A slight phase lag was found at the 0.3 Hz condition, with an increased phase lag at the 0.5 Hz condition, both showing the response to be temporally behind the visual stimulus. Analysis of the phase response revealed no differences between the age groups indicating similar timing responses across the ages of 4, 6, and adult. Furthermore gain variability, along with residsway, was found to decrease with age demonstrating an increased stability in the amplitude response. These results show similar amplitude and timing response patterns between 4-, 6-year-olds and adults, where the developmental differences were seen in the decrease of the gain magnitude and variability, along with a decrease in the residsway. The similarities across age suggest a comparable use of vision for postural control between children and adults, where the children show a more variable response that decreases with age, illustrating changes in the response precision that may be an indication of response tuning.

Response to the dynamic visual stimulus

In a similar study, Schmuckler (1997) presents a hypothesis in which frequency, amplitude, and timing are response parameters that follow different developmental trajectories. The author concludes that the children's response to a dynamic visual stimulus consists of a nonadultlike frequency response and adultlike timing control. Based on this hypothesis the gain response pattern would be expected to change across age corresponding to nonadultlike frequency response. Furthermore, the phase response would be expected to be similar across age groups. Results from the current study show that the response amplitude and timing were similar across age and all show a similar dependence upon the stimulus frequency, suggesting adultlike frequency, amplitude, and timing response patterns. However, comparisons between the current results with Schmuckler (1997) are difficult because of the differences in the stimulus amplitudes used. Schmuckler (1997) utilizes large amplitude movements representing a visual perturbation to the participants whereas the goal of the current study was to characterize responses to small sensory changes individuals experience when interacting with the environment. Due to these differences, an alternative explanation of the current study's results is needed.

Schumway-Cook & Woollacott (1985) hypothesizes a developmental transition period in the use of sensory information for postural control. This hypothesis states that visual inputs dominate postural control early in childhood, from around 4 years of age, whereas at approximately 6 years of age children are able to integrate multiple sensory inputs for postural control. Based upon this hypothesis, the gain and phase response in the present study were expected to be constant across frequency conditions in the visually dominant 4-year-olds, demonstrating a tight coupling to the visual stimulus no matter the variations in the frequency, amplitude and timing. Contrary to these expected findings, the 4-year-old's gain and phase response differed depending upon the stimulus frequency and did not show a constant response across conditions. These discrepancies warrant an alternative explanation of the gain and phase response across frequency.

Both gain and phase profiles found in the present study are qualitatively similar to previous work done with adults in a visual moving room paradigm (Jeka et al. 2000) and interestingly, similar to responses found in a haptic moving room where an oscillating somatosensory stimulus was used (Jeka, Oie, Schöner, Dijkstra, & Henson, 1998; Barela et al., 2003). Model fits performed on the gain and phase values found in

Jeka et al. (1998) suggested that the adults coupled to the position and velocity of the somatosensory stimulus. Although fitting the data in the present study to the model is not possible due to the length of the trials collected (longer trials are necessary to produce reliable model parameters), the similarities in the gain and phase values suggest the possibility that the participants utilized the position and velocity information from the visual stimulus, much like the interpretation of the results found with the somatosensory stimulus. This hypothesis suggests that children as young as age four utilize position and velocity information from the stimulus and changes seen across development may be due to changes in the use of appropriate aspects of sensory information rather than a transition from visual dominance to multisensory integration. Due to the limitations of fitting the data to the model these statements remain speculative and necessitate further work in order to explore this hypothesis.

Prospective control

The positive phase values found in the 0.1 Hz condition was of interest as it indicates a phase lead relationship where the postural response was temporally ahead of the stimulus, demonstrating a prospective aspect of control based upon the frequency of the stimulus. Even the 4- and 6-year-old children in the current study seem to show this prospective control due to the similarities in the children's timing response with the adults. In many situations the postural control system needs to be able to anticipate future actions in order to compensate for factors such as the inertia of the limbs and the neural time lags in order to produce skillful movement (Bertenthal & Clifton, 1998). This leads to the question of how does the control system anticipate the consequence of actions to execute prospective control? One hypothesis could be the control system, through learning, develops an understanding of the physics of the body relative to the environment and is able to calculate based upon sensory information the consequence of movement (Massion, 1998). Another less complicated explanation may be the control systems utilization of the appropriate aspect of the sensory information based upon the relationship between position and velocity. Velocity is defined as the rate of change of position. This relationship dictates that for certain kinds of motion, at peak position, the velocity is at minimum. Furthermore, when velocity is at maximum, position is halfway between peak amplitudes. Therefore maximum velocity must occur before maximum position. Since velocity is based upon position and leads position, it is possible that the utilization of the velocity aspects of sensory information may fulfill the requirements necessary to execute anticipatory actions relative to position information. If this hypothesis were true, the similarities in the timing response across age would indicate that the children may be using velocity information similar to adults in postural control.

Postural response tuning

Bertenthal (1997) describes the changes in the visuomotor control of posture as an increased precision of the stimulus response. In the present study, this response tuning was hypothesized to decrease with age in gain and phase variability, along with a decrease in residual sway not associated with the stimulus frequency. Results showed that both gain variability and residual sway decreased with age demonstrating a more stabilized amplitude response with development. While these results indicate amplitude tuning, the phase variability did not show a change with age. In other words, there is no evidence to support the tuning of the temporal aspects of the postural response. A variable phase response suggests a weak temporal coupling, because the response to the stimulus must be defined in terms of both amplitude and timing. This unexpected finding calls into question the interpretation of postural sway in the moving room paradigm as a continuous use of sensory information.

These findings may be alternatively explained as a consequence of normal sway in front of a stimulus rather than a response to a specific dynamic stimulus. For example, if the results from the present study where due to a consequence of normal quiet standing regardless of the stimulus and not in response to a particular dynamic visual environment, then the gain response pattern across frequency may be due to the changes in the frequency of the stimulus and not because of changes in the sway response. Furthermore the decrease in gain variability and the magnitude of amplitude response may be related to the decrease in residual sway rather than a change in response precision. Due to this confound, it is clear that frequency manipulations alone cannot distinguish between the two possible explanations of these results. One possible approach that may resolve this issue may be to present a stimulus where the frequency is held constant with an amplitude manipulation. Changes in the amplitude of the sway response across variations in stimulus amplitude would indicate that the stimulus influenced the sway response. This clarification is needed in order to interpret the response to the moving room as a utilization of sensory information. Indeed, the second experiment (Chapter IV) addresses this issue.

Summary

This initial experiment characterized the effect of varying visual stimulus frequency on children’s postural response. The results showed the children’s response to be similar to that of the adults but with larger variability. The findings from the present study did not support the hypothesis presented by Schumway-Cook & Woollacott (1985) of a transition period in the development of the postural control system in which children progress from being visually dominant to multisensory capable. Similarities in the child's postural response with the adults suggest an alternative explanation where postural control development may be in part attributed to the ability to utilize appropriate aspects of available sensory information. Furthermore, some evidence for the development of response tuning was shown in an increased precision of the amplitude response. However, this was not seen in the timing of the response allowing two possible explanations of the response to the dynamic visual stimulus as either a coupling of sway and visual information or the age-related changes in quiet stance regardless of a stimulus. Frequency manipulations alone are not enough evidence to distinguish between the two explanations, requiring an extension of the present findings utilizing a stimulus amplitude manipulation to resolve this issue.

CHAPTER IV

AGE-RELATED CHANGES IN THE USE OF VISION FOR POSTURAL CONTROL: THE EFFECTS OF VARYING AMPLITUDE

Introduction

The development of motor actions can be conceptualized, in part, as an increased stabilization or coordination of perception-action relations. An approach commonly used to assess the perception-action system is to characterize the influence of varying sensory inputs on consequent movement responses. For example, quiet standing adults presented with an oscillating visual field will consistently entrain their sway with the motion of the stimulus. That is, a coordinated perception-action system will respond with a distinct and consistent sway response that corresponds with the amplitude and frequency of the visually oscillating stimulus. Furthermore, an adult's postural response will adopt a temporal relationship with the visual stimulus such that sway leads the stimulus at slower frequency oscillations (< ~0.25Hz) and lags behind the stimulus at faster frequency oscillations (> ~ 0.3Hz) (Dijkstra et al. 1994a, b; Jeka et al. 2000). In an analogous task, 4- and 6-yr-old children demonstrate adult-like average amplitude and timing responses, although they have larger within-subject variability than is typically seen in adults (Chapter III). In addition, the amplitude of the frequency components surrounding the stimulus frequency was reduced in these children, illustrating a decrease in the components of sway thought unrelated to the stimulus drive. This reduction of sway, along with the age-related differences in the amplitude and timing of the postural response to a dynamic visual stimulus, are consistent with the notion of response "tuning" across development (Bertenthal et. al. 1997). That is, across development the postural response appears to reflect an increasing precision to dynamic visual stimuli. In this context, "tuning" is described as an improvement in the coordination between the sensory inputs and the motor response as demonstrated by consistent amplitude and timing responses, with reduced sway not associated with the driving stimulus.

In addition to the age-related tuning of the postural response to a dynamic stimulus, developmental differences have been observed in the control of upright stance in the absence of sensory manipulations. For instance, a decrease in the overall variability of the sway trajectory of quiet upright stance has been observed as children age into adulthood (Newell, 1998; Riach et al., 1987) Riach & Hays (1987) characterized the sway trajectory of quiet standing children from two to fourteen years of age and showed that the youngest children demonstrated a broad sway response across the frequency range of 0.05 to 2Hz, with a majority of sway amplitude accounted for within this bandwidth. With increasing age, the children showed less sway at higher frequencies (0.8 to 2Hz) and increased sway at the lower frequencies (>0.8Hz). This result suggests an age-related tendency towards a narrowing and shifting of the frequency bandwidth that accounts for the majority of observed sway variability.

These age-related changes in unperturbed postural control suggest a potential confound to the thesis that age-related changes in quiet stance control are due to a tuning of the perception-action relationship. The observation in both the quiet stance and dynamic stimulus experiments that sway amplitude in the frequency components greater than 0.8Hz are reduced suggests that the reduction of sway in the dynamic stimulus condition may reflect, at least in part, the reduction of unperturbed sway independent of the sensory manipulation. The age-related similarities between experimental tasks in the frequency components less than 0.8Hz also calls into question the interpretation that children have adult-like amplitude responses to visually perturbed stimuli. That is, the amplitude of the response to the sensory cues may be characteristic of normal upright stance relative to the stimulus rather than a reflection of the sensory manipulation. In this scenario, the variability of the amplitude measures would be attributed to general quiet stance postural control rather than the response to the stimulus. While these findings illustrate the lack of clarity in understanding the effects of dynamic visual stimuli on the postural response of developing children, the similarity between the mean timing measures of the child and adult postural responses suggest that visual inputs do influence children's upright stance. Additionally, decreases in the variability of the timing response across development support the notion that the tuning of the postural response is a reflection of the changes occurring in the response to the stimulus (Chapter III). These conflicting interpretations call for experimental clarification to resolve the issue.

One approach to clarify the interpretation is to study the effect of a dynamic stimulus on the postural response by systematically manipulating the amplitude of the stimulus and comparing the response across conditions to see if the changes in the stimulus are reflected in the response. If the sway amplitude is shown to increase above baseline levels with increasing stimulus amplitude, it would suggest that the stimulus had an influence on the sway response. For example, Peterka and Benolken (1995) recorded postural sway in adults who where presented with a dynamic visual stimulus where the frequency of oscillation was kept constant while amplitude was varied from 0.2 to 10 degrees. The results of this study indicated that the adult's sway amplitude increased and eventually reached a saturation level as stimulus amplitude increased, demonstrating vision’s influence on postural sway. If a similar comparison with developing children were to find increases in sway amplitude, it would suggest, as it did in adults that stimulus amplitude influenced the postural sway. However, if the sway amplitude showed no change across stimulus amplitude, it would indicate the stimulus had no effect on the sway response and the children’s results may simply reflect normal quiet standing. Therefore, an amplitude manipulation with children would clarify whether the changes in the response to a dynamic visual stimulus are due to changes in quiet stance control or changes in the response to the dynamic visual stimulus. This same inference cannot be made with frequency manipulations alone due to observed differences in the response attributed to stimulus frequency. Thus, a systematic manipulation of the stimulus amplitude would clarify questions regarding the tuning of the perception-action relationship.

Age-related differences in the postural response to varying stimulus amplitudes between children and adults may indicate age-related differences in the use of vision for the control of posture. Schumway-Cook & Woollacott (1985) suggested a transition period between 4 to 6 years of age in the use of sensory information for the control of posture. According to the authors, vision is the primary source of information used to control posture early in the transition period. By the end of this period, the child is able to integrate inputs from the visual, somatosensory and vestibular systems in an adult-like manner (Shumway-Cook & Woollacott, 1985). If this age range truly represents a transition period, then the 4-year-olds’ postural responses will demonstrate a dependence on the visual stimuli showing clear age-related differences when compared to children 6 years and older. Furthermore, children 6 years and older should show adult-like postural responses according to the hypothesized transition period.

The purpose of the present study is to further examine the tuning of the postural response to a dynamic stimulus and to clarify its relationship with the developmental changes occurring in normal upright stance by comparing the sway response across varying stimulus amplitudes with quiet stance sway relative to a stationary stimulus. We suggest that these changes occurring in normal stance are inherently linked to the postural responses in the dynamic sensory condition and we propose an experiment which will tease apart the postural response due to changes in quiet stance control with those due to changes in the tuning of the perception-action system. An examination of the postural response to varying amplitude conditions will a) test for the possible existence of transition periods in the use of vision for the control of posture as indicated by differences between 4- and 6-year-old children; and, b) clarify whether the changes in the amplitude measures are due to changes in the response to the dynamic stimulus or due to the changes in the sway characteristics of quiet stance. This clarification must be made if the findings from the dynamic stimulus literature are to be used in conjunction with the quiet stance literature to form conclusions about the development of vision’s influence on postural control.

Method

Participants

Thirty participants were included in this study: ten 4-year-olds (M = 4.6, SD = 0.3 years), ten 6-year-olds (M = 6.3, SD = 0.5 years), and ten adults (M = 21.8, SD = 2.1

years). All participants were healthy and normally developing, with normal or corrected vision. Participants were recruited from the University of Maryland community and the surrounding area. Each participant, or in the child's case a parent or guardian, provided written informed consent prior to participation according to procedures approved by the Institutional Review Board at the University of Maryland at College Park (see appendix B for a copy of the consent form).

Experimental Set-Up

Figure 12 illustrates the simulated moving room used to manipulate visual information via computer generated visual display. The static visual display consists of an image of 100 randomly scattered small white triangles on a black background (0.2 degrees X 0.2 degrees). The dynamic visual display was created from this same image, where all points in the visual array moved synchronously in the medio-lateral (ML) direction at the same velocity creating simple horizontal flow. The visual stimulus was generated by a Windows NT workstation (Intergraph TDZ-2000) and back projected onto a translucent screen (2.5m x 1.0m) from a mounted Electrohome™ projector (ECP 4500). The participants wore goggles to limit the field of view to approximately 100 degrees high by 120 degrees wide so that the edges of the screen were not visible.

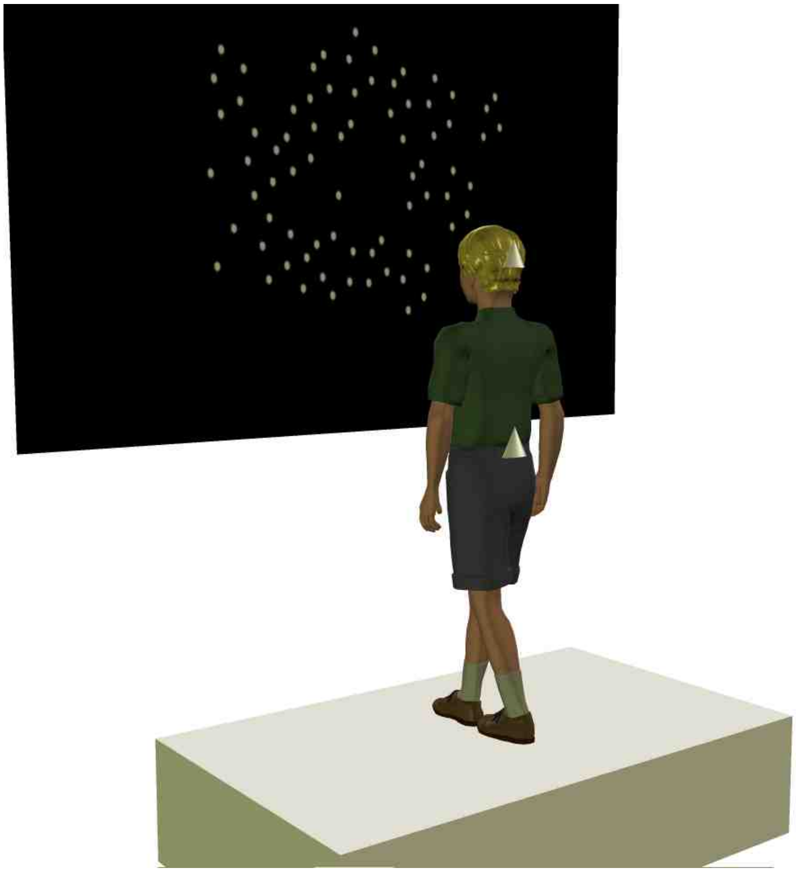

Figure 12. Illustration of the Experimental Setup

To measure the postural response to the visual stimulus in the ML direction, an ultrasonic tracking system (Logitech, Inc.™) was used to measure body sway in 3 dimensions. The system consists of a control unit, a triangular ultrasonic transmitter (25x25x25cm) and two small triangular receivers (7x7x7cm). The participants wore a headband on which one of the receivers was attached to measure the displacement of the head, with the other receiver affixed to a waistband at approximately the 4th or 5th lumbar vertebra to measure body displacement at the approximate center of mass. The transmitter was mounted on a tripod positioned approximately one meter behind the participant and at a height midway between the two receivers during the experimental session. All signals were sampled at 50.33Hz in real time using a National Instruments A/D board (BNC-2090) using a custom LabView data acquisition program.

Experimental Design

The experimental design consisted of 3 dynamic and 1 static visual stimuli conditions. In the dynamic conditions, the visual stimuli moved as a whole laterally with amplitudes of 2, 5 and 8 mm at a constant frequency of 0.3Hz. In the static condition the visual stimulus remained stationary for the duration of the trial. The stimulus conditions were presented in randomized blocks of trials across subjects where each block consisted of one trial from each of the 4 conditions. Three 60s trials were collected in each of the conditions for a total of 12 trials (4 conditions x 3 trials). The total time for an experimental session was 1.5 hours including breaks.

Procedure

Once acclimated to the laboratory environment, the participants were asked to stand quietly in a modified tandem stance (with the toe touching the medial side of the heel) 40cm from the screen. At the beginning of a trial, the stimulus appeared along with a small image of a clock. The clock image then disappeared at the start of the trial when the stimulus began oscillating. When the trial was over, the clock reappeared and disappeared again when the next trial started. The participant was asked to attend to the screen and report when the clock disappeared and reappeared to keep the participant on task. A break was given between trials and at the end of the testing session the participant received a prize.

Data Analysis

ML sway data and the position of the visual stimulus were first detrended by subtracting the mean of each signal to remove DC offset and filtered with a recursive 4th order 5Hz lowpass Butterworth filter. The transfer function (frequency-response function) for each data segment was calculated by taking the cross power spectrum of the stimulus and the sway and dividing it by the power spectrum of the stimulus. This computation of the transfer function is theoretically equivalent to the Fourier transform of the sway divided by the Fourier transform of the stimulus. For each data segment in the dynamic condition, four measures were recovered for both the head and approximate center of mass (CoM): gain, phase, residual power spectral density (residsway) and stimulus frequency sway amplitude (SFSA). For the static condition, only the residsway and SFSA for each segment were calculated.

Measures

Gain is defined as the ratio between the body sway amplitude and the visual stimulus amplitude at the driving frequency (0.3Hz). Gain represents the strength of the postural response relative to the stimulus and will be calculated as the absolute value of the transfer function at the stimulus frequency. Gain values of close to 1 represent body sway amplitude that is approximately equal to the visual stimulus amplitude at the driving frequency. Values lower than 1 represent a body sway amplitude that is less than the stimulus amplitude, and values greater than 1 represent a body sway amplitude that is greater than the stimulus amplitude. We hypothesize that the mean gain values will be dependent upon the amplitude condition presented based upon the work done by Peterka and Benolken (1995) showing a decreased response with increasing amplitude. Furthermore, decreased gain variability across age will indicate a response tuning demonstrating an increased amplitude response precision. Based upon the hypothesized transition period the gain response in the 4-year-olds would be expected to remain constant across amplitude conditions, indicating a tight amplitude coupling regardless of stimulus amplitude. This type of linear response reflects proportional changes in the sway response relative to the changes in the amplitude of the stimulus. This result would indicate that the 4-year-olds were visually dominant in the amplitude parameters of the postural response to the dynamic stimulus.

Phase is the normalized representation of the timing between the body sway and the visual stimulus, recovered as the complex value of the transfer function at the stimulus frequency. A phase value of zero represents no time delay between the response and the stimulus. Phase values greater than zero represents body sway leading the stimulus, with phase values below zero representing body sway lagging behind the stimulus. We hypothesize the phase values to be constant across amplitude conditions because stimulus frequency is held constant, while a decrease in phase variability with age will indicate an increased temporal precision to the dynamic stimulus. Based upon Shumway-Cook and Woollacott's notion of a transition period between 4 and 6 years of age, we would also expect 4-year-olds to exhibit constant phase across all amplitude conditions. However, proponents of this hypothesis would also suggest a similar phase response to any stimulus frequency based upon the notion that early in the transition period shows a visual dominance where the sway will show changes proportional to the changes in the stimulus.

The stimulus frequency sway amplitude (SFSA) is the point on the sway response power spectrum corresponding to the frequency of the stimulus (0.3Hz). The SFSA represents the average power of the component of sway at the stimulus frequency and is represented in the gain ratio as the numerator. The SFSA was calculated for both the dynamic and static conditions. We predict that if the postural sway in the dynamic conditions reflects a utilization of the stimulus, the SFSA response in the amplitude conditions should all differ from the static condition. Conversely, if the postural sway in the dynamic condition is not in response to the stimulus, the SFSA response in the static condition should not differ from the amplitude conditions. Once the SFSA response is assessed, the gain response can be interpreted to reflect either a response to the stimulus or simply a consequence of general postural sway. Across age, SFSA variability is expected to decrease with age, indicating an increased stabilization of the amplitude response characteristic of amplitude response tuning.

ResidualPSD quantifies the amount of sway which lies in the frequency components surrounding the frequency of the stimulus (0.3Hz). ResidualPSD is calculated by combining the power in the bandwidths below and above the stimulus frequency, in effect filtering out the 0.3Hz component of sway. ResidualPSD represents body sway with the influence of the visual drive removed and was calculated for both the dynamic and static conditions. A decrease in residsway with age would indicate a response tuning, showing increased response precision to the visual stimulus.

Statistical Analysis

For the measures of SFSA and residsway, individual 3x4 MANOVA (age and condition) with repeated measures on condition was utilized as a test of significance with age (4, 6 and adult) and the four stimuli conditions (2, 4, 8mm and static). Univariate repeated measures ANOVAs were used to follow up significant effects. For each of the dependent measures of gain and phase, a 3x3 MANOVA (age and amplitude) for the three amplitudes (2, 4, 8mm) was utilized, followed by appropriate univariate repeated measures ANOVA. Data from both the head and CoM was included in each MANOVA. Significant effects were followed by LSD post-hoc procedures. Level of significance was set at 0.05 for all main effects and interactions.

Results

The results are divided into two sections. The first section addresses the question of whether the changes in the response to the dynamic visual stimulus were due to the tuning of the response, or a consequence of normal quiet stance development. This section includes the analysis of the amplitude (gain, SFSA and timing (phase) of the response. The second section contains results characterizing the tuning of the response across age, which includes the amplitude response variability (gain STD SFSA STD), timing variability (phase std), and residual sway power (residsway).

The moving room response: Is it real?

Amplitude response

The first analysis tested gain in order to assess the response amplitude as a function of visual stimulus amplitude (2, 5, and 8mm) and age (4-yr, 6-yr, and adult).

Repeated measures MANOVA revealed a significant main effect for both head and CoM for amplitude ($F(4,24)=13.28$, $p<0.05$), age ($F(4,52)=3.10$, $p<0.05$), and an amplitude by age interaction ($F(8,50)=4.36$, $p<0.05$) which shows that the gain response across amplitude conditions depended upon age. Follow up univariate analysis for the head (Figure 13) revealed an amplitude effect ($F(2,54)=24.38$, $p<0.05$), and an amplitude by age interaction ($F(4,54)=5.3$, $p<0.05$) and the CoM (Figure 14) revealed an amplitude ($F(2,54)=39.28$, $p<0.05$) and an age by amplitude interaction ($F(4,54)=12.98$, $p<0.05$) Post-hoc analysis for both the head and center of mass showed 4-year-olds responding differently than the 6-year-olds and the adults when comparing changes in gain between the 2mm and the 5mm conditions, and between the 2mm and the 8mm conditions. All age groups responded similarly in the comparison between the 5mm with the 8mm condition. Further post-hoc comparisons of the amplitude effects within age for the head revealed: the 4-year-olds gain in the 2mm condition was significantly greater than the 5 and 8mm conditions; the 6-year-olds gain in the 8mm condition was significantly lower than the other two conditions; and the adults gain showed a significant decrease when comparing the 2mm and the 8mm condition. Gain from the CoM showed similar results, except the 6-year-olds showed significant differences only in the comparison between the 2mm and the 8mm condition.

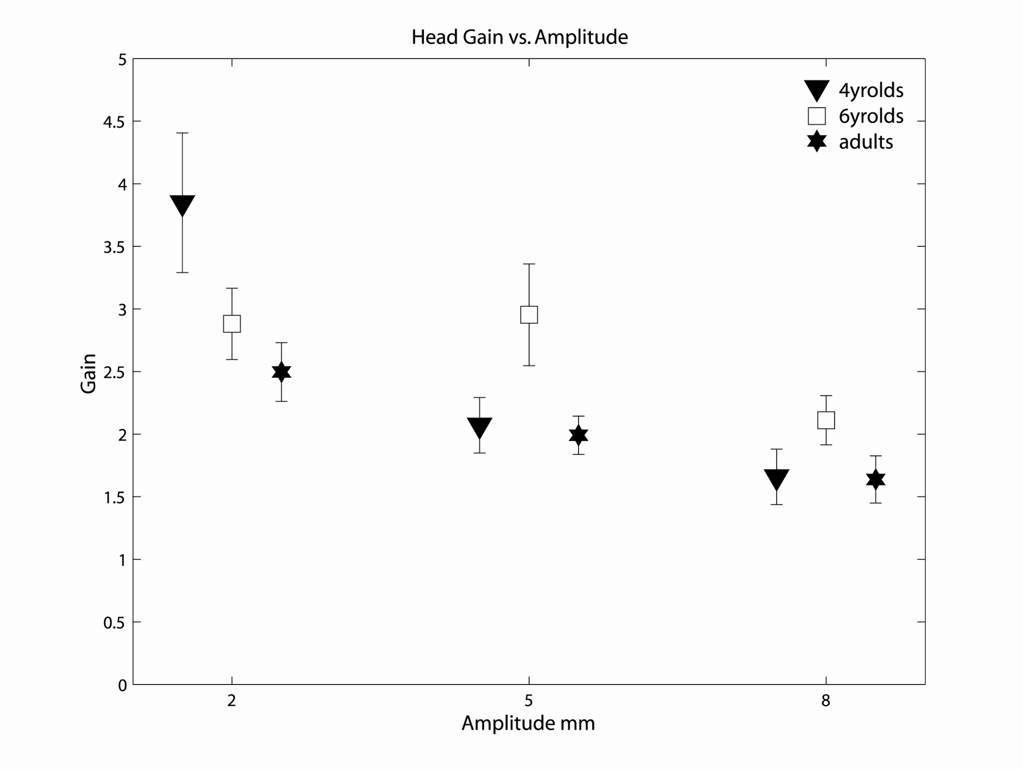

Figure 13. Mean Gain Values and the Standard Error of the Mean for the Head Across Amplitude

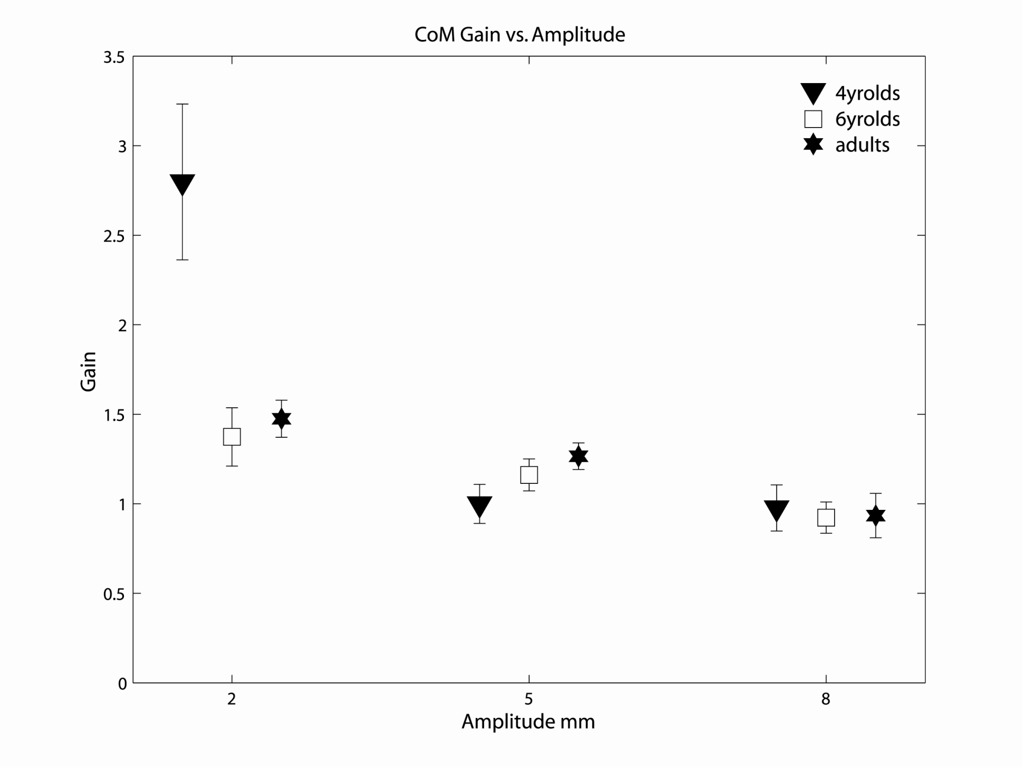

Figure 14. Mean Gain Values and the Standard Error of the Mean for the CoM Across Amplitude

In order to interpret the gain response as either a utilization of the visual stimulus, or a consequence of normal sway relative to the stimulus, SFSA was assessed for each age group and amplitude condition, including the static condition. Repeated measures MANOVA revealed a significant main effect for amplitude ($F(6,22)=33.52$, $p<0.05$) for age ($F(4,52)=2.64$, $p<0.05$) and a amplitude by age interaction ($F(12,46)=6.47$, $p<0.05$). The age by amplitude interaction revealed the SFSA response across amplitude to be dependent upon age. Follow up univariate analysis of the head (Figure 15) revealed an amplitude ($F(3,81)=89.52$, $p<0.05$) and an age by amplitude interaction ($F(6,81)=5.55$, $p<0.05$), while the CoM (Figure 16) also revealed an amplitude ($F(3,81)=67.63$, $p<0.05$) and an age by amplitude interaction ($F(6,81)=6.74$, $p<0.05$). Post-hoc analysis of the interaction for the head and center of mass revealed that all age groups responded similarly in the comparison between the static and the 2mm condition. Furthermore, the 4-year-olds where shown to have responded differently from the other age groups in the comparison between the static and the 5mm condition, and between the static condition and the 8mm condition. Further comparisons of the 4-year-olds SFSA response from the head revealed no significant differences between the static condition and the 2mm condition, with an increase across the 2, 5, and 8mm amplitude conditions. Post-hoc analysis of the CoM showed a SFSA response that was significantly greater in the 8mm than the other conditions. The 6-year-olds head SFSA showed no difference between the static and the 2mm condition, with an increase in SFSA from the 2mm to the 5mm condition, and no significant differences between the 5mm and the 8mm conditions. The CoM also showed no difference between the static and the 2mm condition, with an increase in SFSA as a function of stimulus amplitude. The adult's SFSA response from the head increased across all conditions, where the CoM showed a similar increase, except no significant difference was found in the comparison between the 5mm and the 8mm conditions.

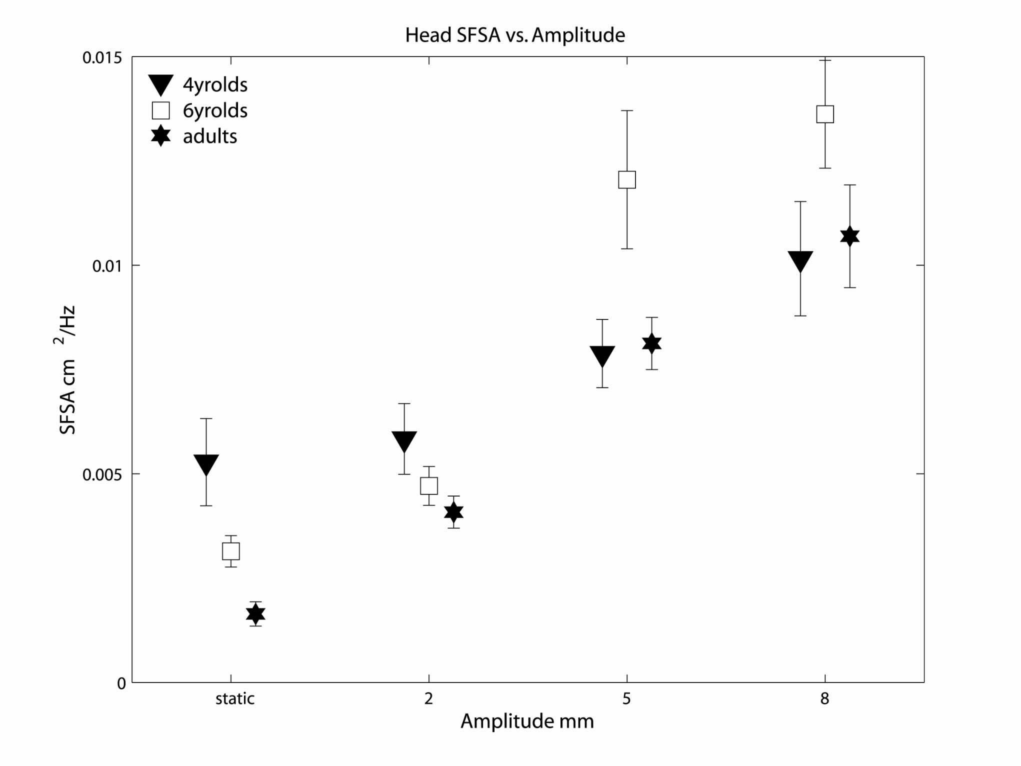

Figure 15. Mean SFSA Values and the Standard Error of the Mean for the Head SFSA Across Amplitude

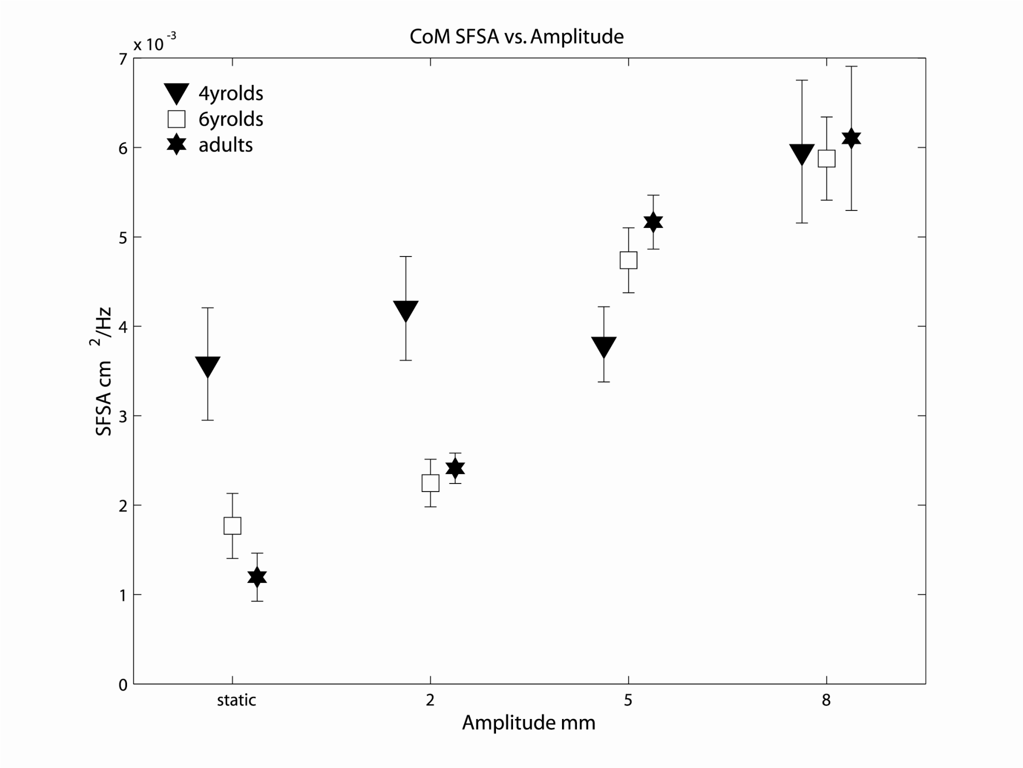

Figure 16. Mean Values and the Standard Error of the Mean for the CoM SFSA Across Amplitude

Timing response

To assess the timing of the postural response relative to the stimulus, phase was calculated for each age group and amplitude. Repeated measures MANOVA revealed a significant main effect for amplitude ($F(4,24)=5.38$, $p<0.05$) and an amplitude by age interaction ($F(8,50)=4.12$, $p<0.05$). Follow up univariate analysis showed a condition effect for the CoM (Figure 18) ($F(2,81)=4.87$, $p<0.05$) with no interaction, and an age effect for the head (Figure 17) ($F(2,81)=3.94$, $p<0.05$) with no interaction. Post hoc comparisons for the CoM showed that the 2mm condition was significantly lower than the other conditions indicating a phase lag response, while the age comparisons for the head showed 4-year-olds had a reduced phase lag response compared to the other ages.

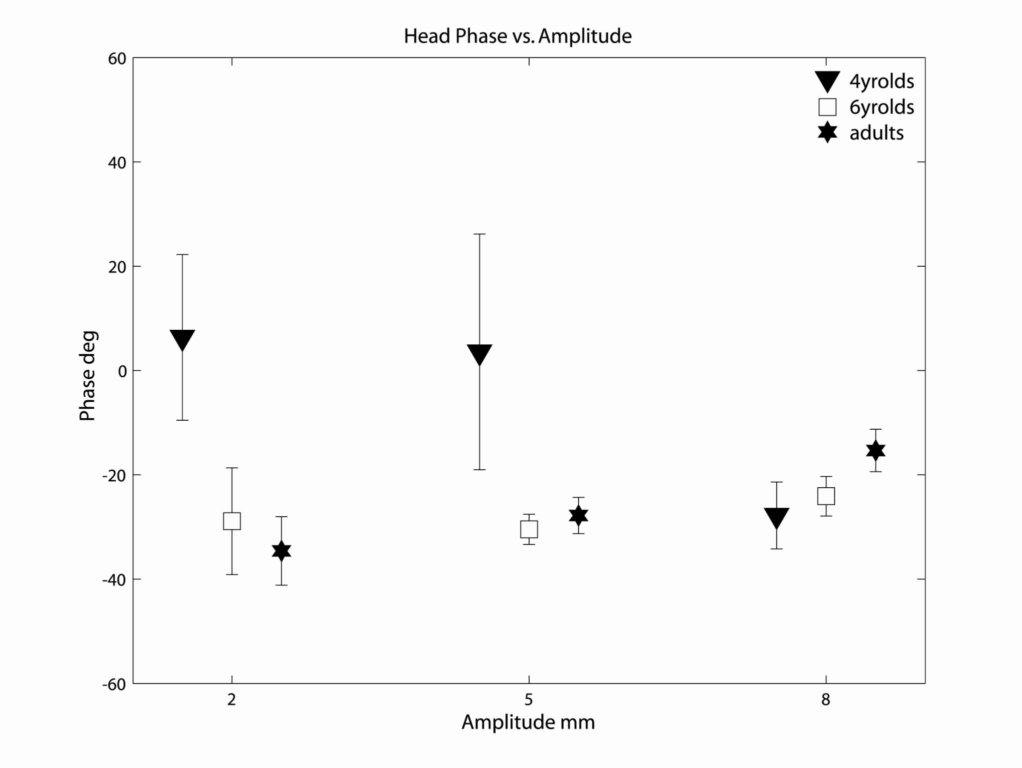

Figure 18. Mean Phase Values and the Standard Error of the Mean for the Head Across Amplitude

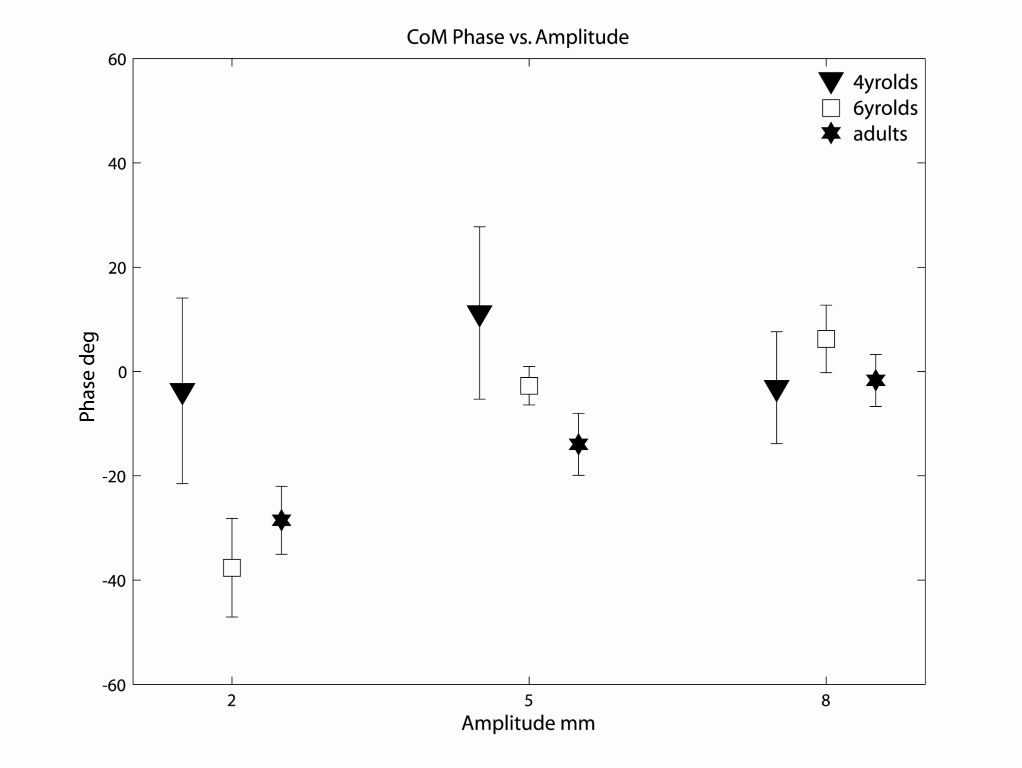

Figure 17. Mean Phase Values and the Standard Error of the Mean for the CoM Across Amplitude

Perception/action tuning

Amplitude variability

The next analysis evaluated gain variability (Figure 19 and Figure 20) as it reflects the tuning of the response to the visual stimulus. A significant main effect for age (*F*(4,52)=6.175, $p<0.05$) was found in gain's standard deviations of the mean. Post hoc analysis revealed that the 4- and 6-year-olds responded similarly, but differed from the adults, with the children showing larger gain variability than the adults.

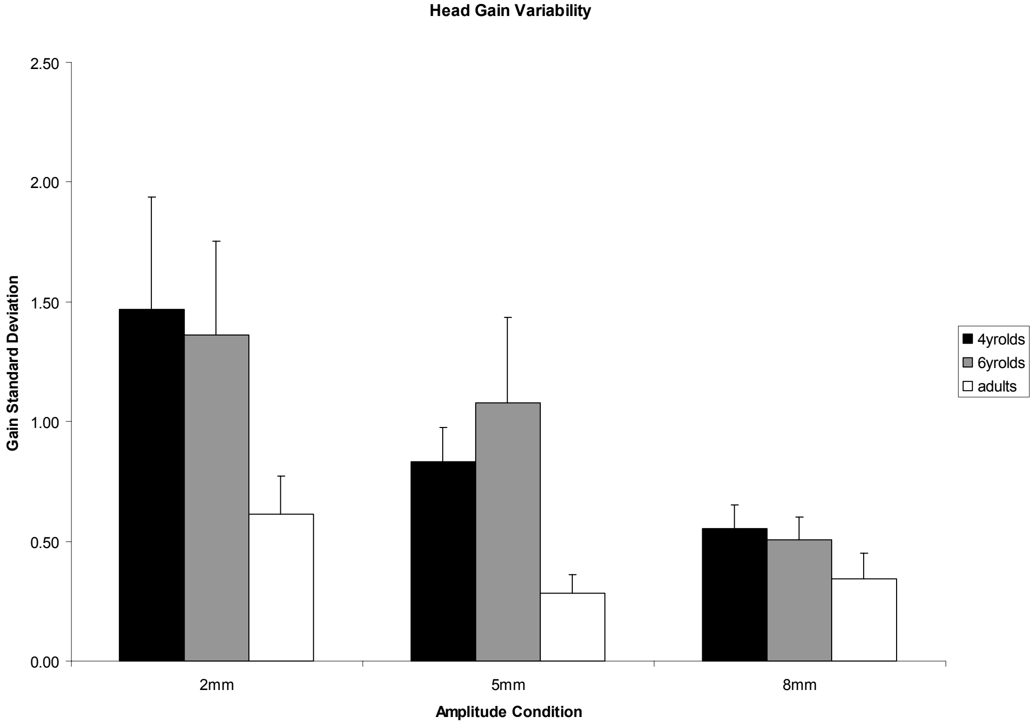

Figure 19. Standard Deviation of the Head Gain Across Amplitude

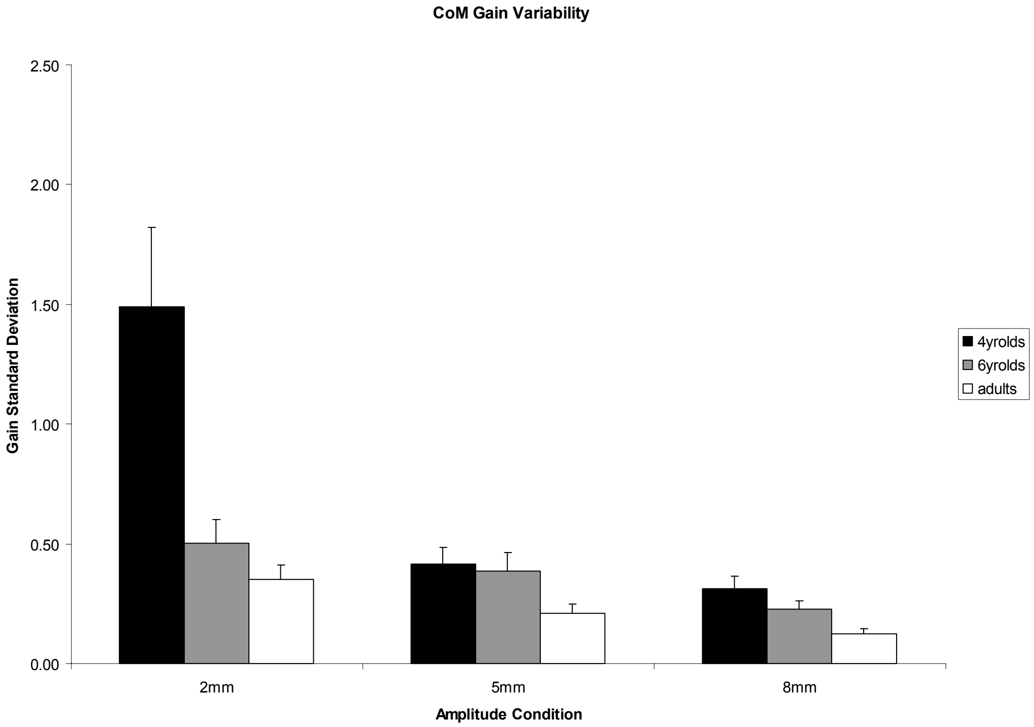

Figure 20. Standard Deviation of the CoM Gain Across Amplitude

Similar to gain variability, the measurements of SFSA variability are of interest as it pertains to the tuning of the postural response (Figure 21 and Figure 22). MANOVA revealed a significant main effect for age (*F*(4,52)=7.50, *p*<0.05) in the SFSA's standard deviations of the mean. Post hoc analysis shows that in both the head and CoM the 4- and 6-year-olds responded similarly and both had larger variability than adults.

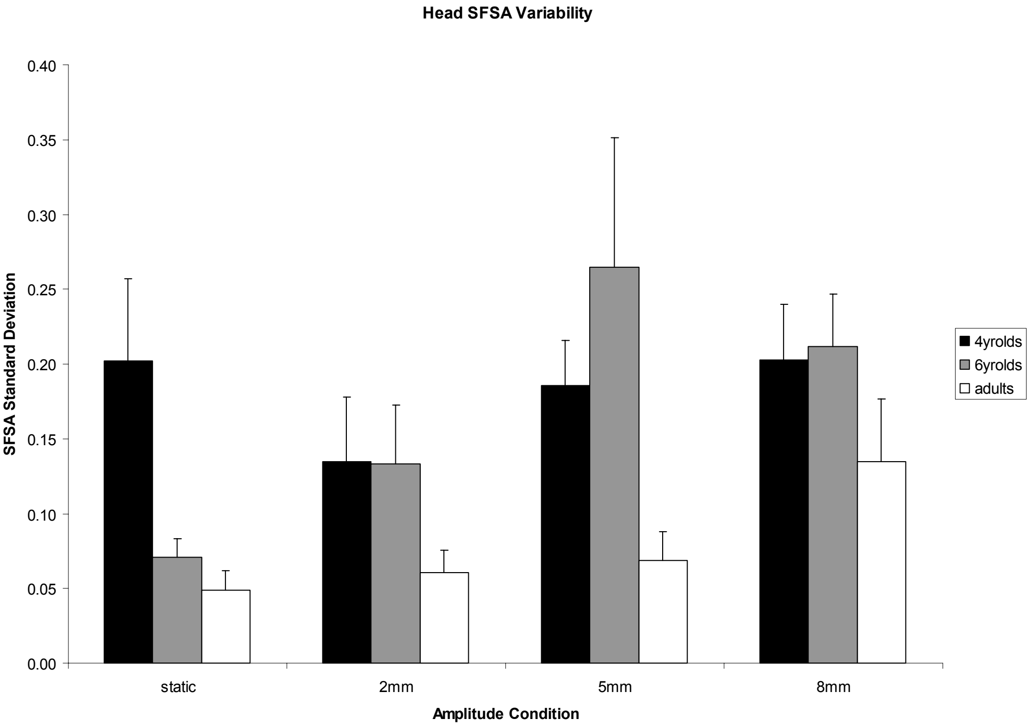

Figure 22. Standard Deviation of the Head SFSA Across Amplitude

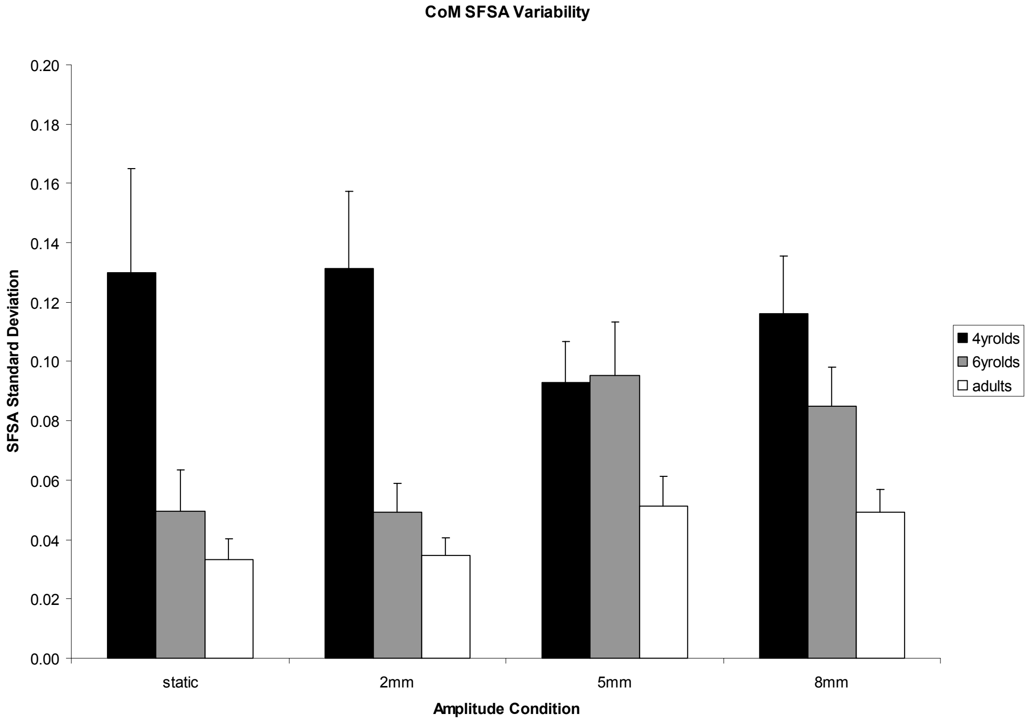

Figure 21. Standard Deviation of the CoM SFSA Across Amplitude

Timing variability

The next analysis assessed phase variability to characterize the stability of the response timing. A significant main effect for age ($F(4,54)=6.06$, $p<0.05$), amplitude ($F(4,24)=7.38$, $p<0.05$), and a amplitude by age interaction ($F(8,50)=3.83$, $p<0.05$) was found. Follow up univariate analysis for the head (Figure 23) shows an age effect ($F(2,27)=12.96$, $p<0.05$), amplitude effect ($F(2,54)=9.56$, $p<0.05$), with no age by amplitude interaction. Analysis of the CoM (Figure 24) also shows an effect for age ($F(2,27)=16.97$, $p<0.05$), condition ($F(2,54)=6.90$, $p<0.05$), with no interaction. Post-hoc comparisons for the head with respect to condition shows the 2mm condition was significantly larger variability than the other two amplitudes, while the age comparisons for the head revealed the 4-year-olds were significantly more variable than the other age groups. The comparisons for the CoM resulted in similar findings.

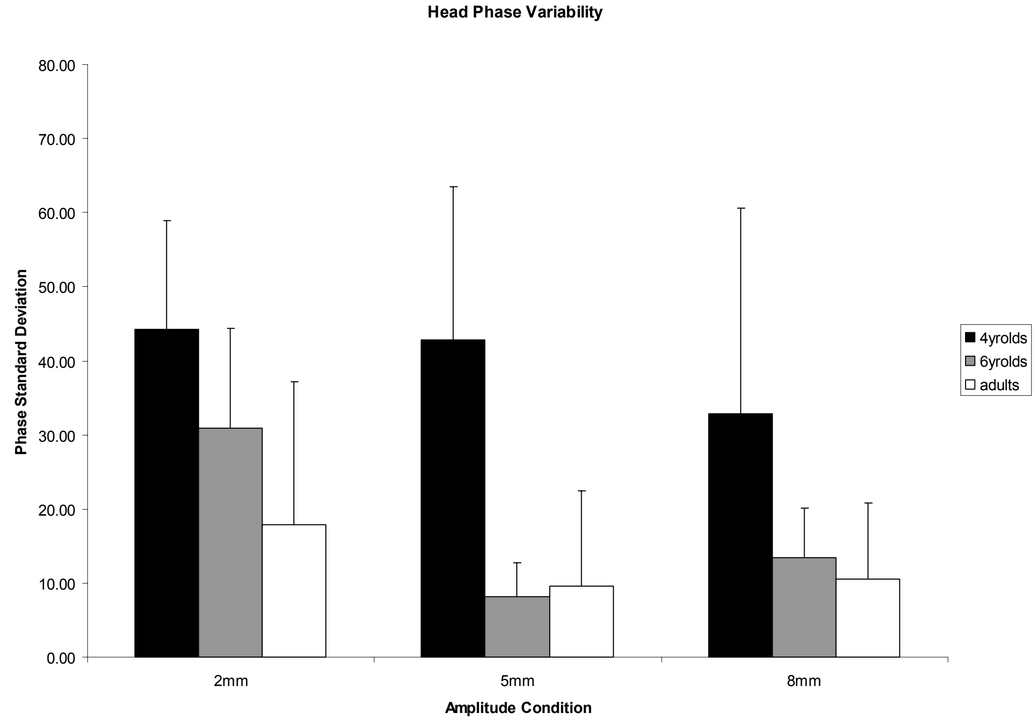

Figure 24. Standard Deviation of the Head Phase Across Amplitude

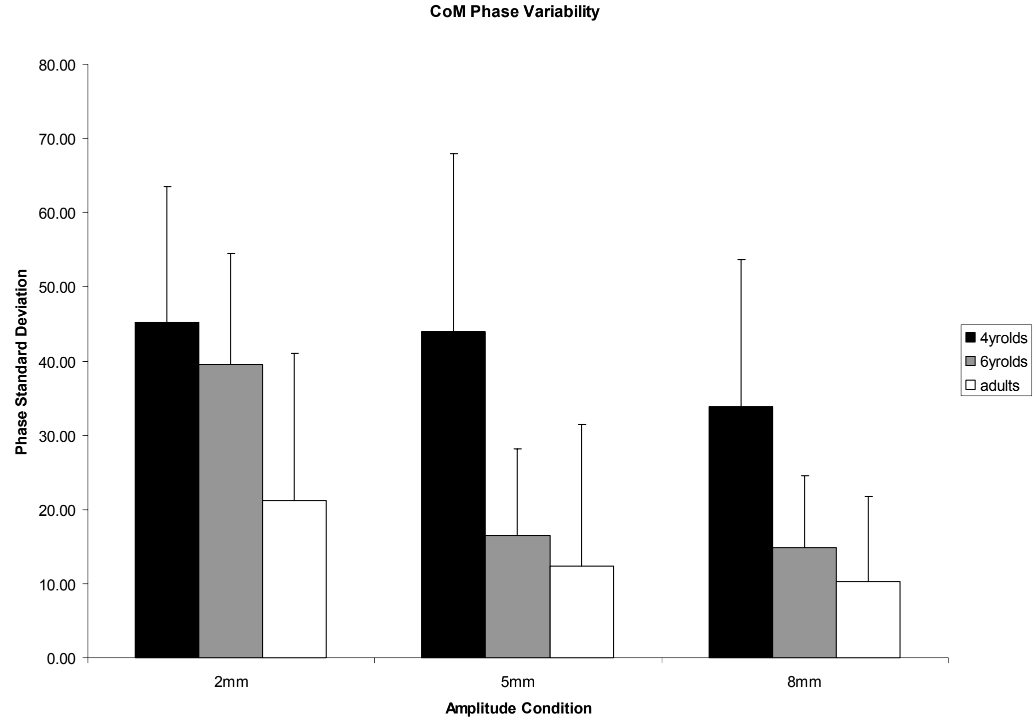

Figure 23. Standard Deviation of the CoM Phase Across Amplitude

Sway variability

To further characterize the response tuning, residsway was calculated for each condition and age group (Figure 25 and Figure 26). Repeated measures MANOVA revealed a significant main effect for age (*F*(4,52)=10.15, *p*<0.05), but not for amplitude (*F*(6,22)=1.85, *p*>0.05). The age by amplitude interaction was not significant. The age main effect shows a decrease in residsway with increasing age, revealing a decrease in sway not associated with the visual drive, consistent with the notion of a response tuning across development.

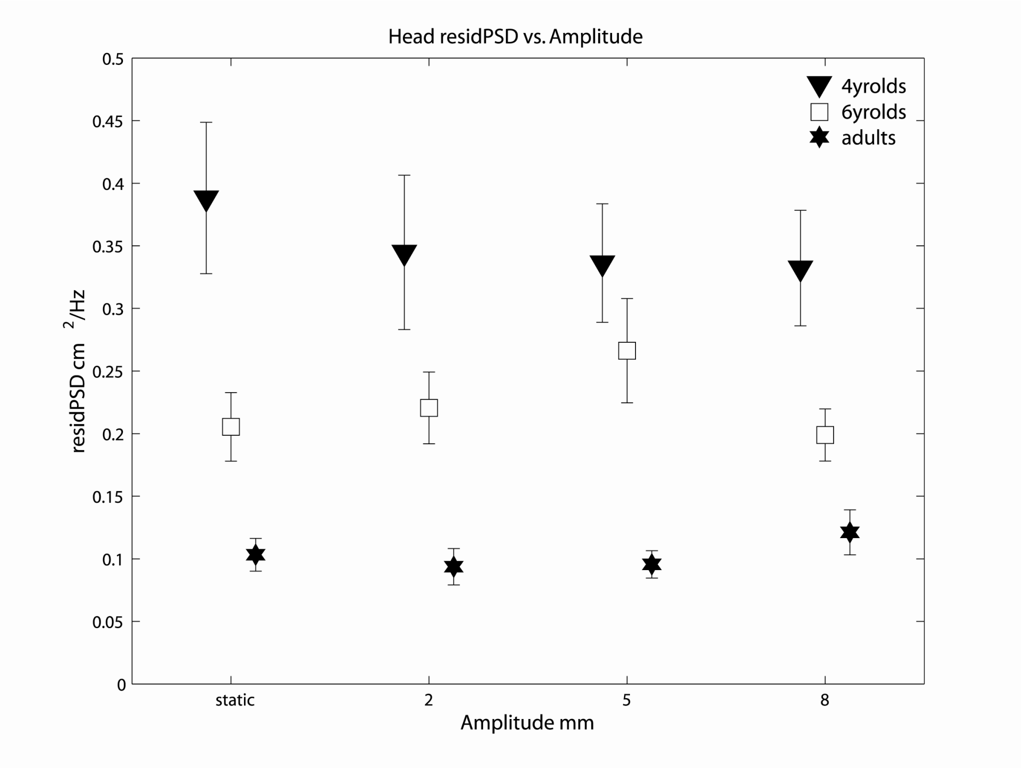

Figure 25. Mean residsway Values and the Standard Error of the Mean for the Head Across Amplitude

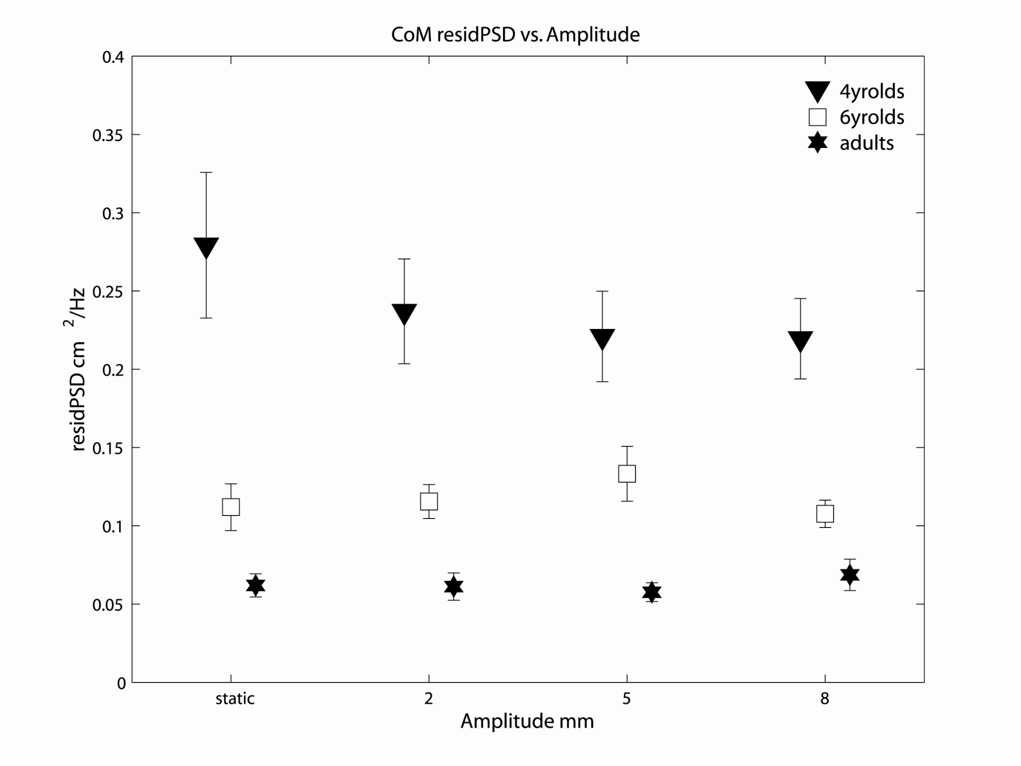

Figure 26. Mean residsway Values and the Standard Error of the Mean for the CoM Across Amplitude

Discussion

The present study examined the effect of varying visual stimulus amplitude on the postural response in children to determine if the changes in the moving room response are due to a response tuning, or a consequence of normal quiet stance development. Results showed the amplitude of the postural response increased as a function of increasing visual stimulus amplitude, elevating to levels above baseline sway. This finding suggest that the visual stimulus influenced the postural sway and that the moving room response is not purely the coincidence of normal stance sway in front of a stimulus, but rather a utilization of sensory information. Further examination of the amplitude response reveals a non-linearity in the sway response with increasing stimulus amplitude that differed depending upon age. Lastly, decreases in both the amplitude and timing variability along with the decrease in sway not associated with the stimulus frequency, show increased response precision with age. This finding illustrates the changes in the stability of the response across age, describing the postural response tuning. Each of these issues are discussed below.

Moving Room Response: Is It Real?

The results of the SFSA analysis indicated that as the visual stimulus amplitude was increased, the amplitude of the postural response increased for all age groups, suggesting that the stimulus influenced postural sway. Furthermore, the trajectory of the SFSA response as a function of amplitude differed for each age group as indicated by the interaction between the two variables. For example, both the 4- and the 6-year-olds showed no significant differences between the static condition and the 2mm condition, whereas the adults showed an increase across the two conditions. One possible explanation for this may come from the fact that the younger 4- and 6-year-olds generally showed larger amounts of baseline sway than the adults did, that may have masked the small 2mm amplitude stimulus. In other words, the 2mm amplitude condition may not have been large enough relative to the children's sway to have been detected with the SFSA measure.

This may also in part explain the timing response at the 2mm condition. Phase showed the largest variability at the 2mm condition, making it difficult to interpret the amplitude response at that condition because the response must be defined in terms of frequency, amplitude and timing. If the timing relationship is variable, the response amplitude could be explained as coincidence rather than responding to the stimulus. In spite of this finding, phase at the 5mm and 8mm conditions was shown to have been more stable, and indicated that the participants adopted the same temporal patterns across the two amplitudes, which was expected because the stimulus frequency was kept constant throughout the experiment. This type of stable phase response supports the notion that the amplitude response was due to the changing visual stimulus, and not coincident, within the 5mm and 8mm conditions.

Sensory Information: How is it being used?

Results of the current study found the gain values to be dependent upon amplitude condition. This gain profile indicated a non-linear response, where sway amplitude did not increase in proportion to the increases in stimulus amplitude, resulting in different gain values for each condition (Oie, Kiemel, & Jeka, 2001). This finding is contrary to the hypothesized transition period of visual dominance to multisensory capability, rather this non-linear response may be an indication of a sensory re-weighting, where the postural control system dynamically re-weights multiple sensory inputs to maintain upright stance as sensory conditions change (Horak & Macpherson, 1996). This appears to be present even in the 4-year-olds and casts further doubt on the hypothesized transition period. The postural control system must be flexible as individuals interact with the environment as they encounter many small changes in sensory conditions, which in some cases cause ambiguity if changes in one sensory input are not detected in other sensory systems. For example, standing on a street corner, a change from a red to a green light will cause objects in the environment (cars) to create a large visual flow. The control system may interpret this visual information as self-motion, whereas somatosensory and vestibular inputs do not reflect this visual information. To maintain balance, the control system may need to minimize the visual information and maximize the other inputs as valid information (Collins & De Luca, 1995). In other words flexible balance control requires the ability to adjust the weights to different inputs based upon changes in the sensory environment. The non-linear gain response found in the current study may be a result of the control system recognizing the large amplitude stimulus as non-veridical and re-weights the visual input, causing an amplitude response that was not as large in proportion to the stimulus as the other smaller conditions.

The re-weighting hypothesis implies a scheme to determine the optimal shifts in sensory weights. Schöner et al. (1998) suggested a categorization scheme where the nervous system labels small amplitude stimuli as self-motion, whereas large amplitude motion is seen as object motion within the environment. An input viewed as being object motion would result in setting that weight low because it is a less reliable indicator of self motion (Schöner, Dijkstra, & Jeka, 1998). One example of how this process can be achieved comes from previous work in adults that has shown a saturation effect such that an increase in stimulus amplitude past a certain threshold level did not evoke increases in postural sway (van Asten, Gielen, & Denier van der Gon JJ, 1988; Lestienne et al., 1977). Peterka & Benolken (1995) did one such study in a comparison between normal participants and bilateral vestibular patients and found that the normals showed the saturation effect, while the vestibular patients did not. With increases in stimulus amplitude, the vestibular patients where found to increase there sway until falling. This suggests that the sensory cues that caused this saturation where of vestibular origin. Furthermore, both groups performed similarly until the stimulus amplitude reached the saturation point, suggesting a threshold where visual and vestibular inputs are re-weighted in order to maintain balance. It is possible that this saturation effect is a reflection of the re-weighting process between the visual and vestibular inputs as a function of visual stimulus amplitude (Nashner, Black, & Wall, III, 1982).

In the current study, a saturation effect was not seen in the measure of SFSA. One possible reason could be that the amplitudes used were not large enough to surpass the vestibular threshold. The largest amplitude used in this study was 8mm, well within the bounds of stability for both the children and adults. Hypothetically if the current study included larger stimulus amplitudes, saturation would be expected. One other factor may have been the frequency of the stimulus. Peterka & Benolken (1995) showed the saturation point to be depended upon the stimulus frequency, where increases in frequency decreased the saturation point. The combination of frequency and amplitudes used in the current study may not have been optimal for creating sway saturation.

It is also interesting to note here that both amplitude measures (gain, SFSA) showed different responses across amplitude conditions as indicated by the interaction. Although the responses qualitatively looked similar, differences were seen. With regards to the re-weighing hypothesis discussed above, one explanation may be that the mechanisms for sensory re-weighting may not be fully developed in the younger children (Shumway-Cook & Woollacott, 1995). Schumway-Cook & Woollacott (1985) suggested a transition period between 4 to 6 years of age in the use of sensory information for the control of posture. According to the authors, vision is the primary source of information used to control posture early in the transition period. By the end of this period the child is able to integrate inputs from the visual, somatosensory and vestibular systems in an adult-like manner. According to this hypothesis, the re-weighting process may not be able to available until after the transition period when the child is able to use sensory information in an integrated fashion.

Tuning of the postural response

Bertenthal et al (1997) describes the changes in the visuomotor control of posture as an increased precision of the coupling between perception and action, a tuning of the postural response across age. The results of the study showed this response tuning to the visual stimulus as a decrease in the amplitude and timing variability, with a decrease in sway not associated with the drive. How does the control system change to create these tuning effects in postural sway with age? Some insight into this question may come from a feedback control model of upright stance.

Peterka (2000) utilizes a model consisting of an inverted pendulum with corrective torques applied to the ankle to describe sway. This model uses an error signal (desired state-actual state) detected by sensory inputs to create these torques. These torques are scaled with a proportional, integral, derivative controller (PID) based upon feedback information on position, velocity, and integral of sway. Simulations of this model with varying weights for the position, velocity and integral parameters produced a number of sway profiles some that resemble healthy adults and some that contained large amounts of variability, similar to what is seen in children's sway. Based upon these findings, it may be possible that the tuning process may lie within the optimal selection of the sensory weights with age. Added complexities to this sensory tuning process include the changes in the mechanical system being controlled. This tuning process must take into account the growth and change of body proportions occurring in development

(McCollum et al., 1989). This would be akin to changing the parameters of the inverted pendulum in the model discussed above. Changes in the sensory weights need to be based upon the current properties of the mechanical system, therefore if the mechanical system changes, the sensory weights need to change as well. Both need to be accounted for to produce stable postural control.

Summary

The results from the present study indicate that the postural response to a dynamic visual stimulus may be characterized as a visuomotor response that with development appears to show improvements in the precision of the response amplitude and the timing. These findings did not support the hypothetical transition period proposed by Schumway-Cook & Woollacott (1985) where postural control development is seen as going from visual dominance to multisensory capable. Rather the results suggest that age-related tuning changes may be in part due to the ability to utilize appropriate aspects of the sensory information provided.

Chapter V

General Discussion

When presented with a visual stimulus oscillating at varying frequencies, children's responses depend upon the frequency of the stimulus as shown in similar studies with adults. Furthermore, the gain variability and residual sway decreased with increasing age showing an increased response precision with age. When the frequency of oscillation was held constant and the amplitude was manipulated, the children's postural response increased with increasing stimulus amplitude to levels above baseline sway, demonstrating vision's influence on sway. The response variability decreased with increasing age, again showing the increased response precision with development.

Taken together, the findings from these two studies lead to several generalizations. The first is that the response to the dynamic visual stimuli (i.e., moving room) is a reflection of the use of visual information for postural control, and is not simply a consequence of normal postural sway in children. Our findings confirm this interpretation, which allows for an explanation of the effects stimulus frequency and amplitude manipulations had on sway in terms of sensorimotor control.

The second generalization is that the coordination between vision and the motor response appear to show improvements with development. This was evident in our findings as an increased stabilization of the amplitude and timing parameters of the response, along with a decrease in residual sway with age, indicating a postural response tuning. This tuning process indicates a change in the use of visual information for postural control with development.

Lastly, the children's response amplitude and timing in both the frequency and amplitude manipulations do not support Shumway-Cook & Woollacott's hypothesis (1985) that characterizes 4-year-olds as visually dominant while 6-year-olds are considered multisensory capable in terms of the use of sensory information for postural control. The children's amplitude and timing responses to a dynamic visual stimulus, along with the age-related tuning changes observed suggest that the events occurring during this period of development may not be a transition from visual dominance to multisensory integration capabilities, but rather learning to utilize the appropriate aspects of the sensory information available.

Chapter VI

Recommendations for Future Studies

In the current study we found the children's response to dynamic visual stimuli can be characterized as a utilization of visual information for postural control, rather than a coincidence of normal quiet stance in front of the oscillating stimulus. Furthermore, age-related improvements in the response precision were found to be consistent with the notion of a response tuning with development. In this last chapter we discuss further studies on vision's influence on postural control based upon the preceding findings to extend our knowledge of postural control development.

When observing the effects of varying stimulus frequency on postural sway, we were limited in the number of stimulus frequencies presented due to the number of trials that could be collected within a reasonable length of time for the children before fatigue, boredom, and inattentiveness become factors. Although the frequencies used did provide an initial understanding of its effects on postural sway, it did not allow us to observe the response beyond this frequency range and were limited to hypotheses based on qualitative interpolations. Based upon previous work (Jeka et al, 2000), we expect that if higher frequencies were used we would see gain values decrease with increasing frequency. Deviations from this trend (e.g. consistent or increased gain across frequencies) would suggest changes in the use of visual information with respect to the response amplitude with development. Furthermore, we would expect phase to show an increased phase lag with increasing frequency. Deviations from this hypothesized result would again indicate changes in the temporal structure of the response with development.

The characterization of the stimulus amplitude effects were also limited in the number of amplitudes presented to the children again owing to fatigue, inattentiveness, and boredom concerns. Although the amplitude range used demonstrated vision's influence on the sway response, we did not observe a saturation of sway amplitude as seen in previous work. Based upon Peterka & Benolken (1995), we would expect that if larger amplitudes were used, we would see a saturation point in the sway response. If children are shown to have a different saturation point when compared to adults, it would imply changes in the use of sensory information for postural control across development. One other influential factor may be the frequency at which the amplitude manipulation is performed. Peterka & Benolken (1995) showed that the saturation point depended upon frequency, therefore, further studies utilizing varying frequency and amplitude manipulations combined may uncover developmental changes in the optimal parameters necessary to elicit the saturation phenomenon.

The trial lengths in the current study were constrained to limit fatigue, boredom, and attention issues in the child participants. Unfortunately, this restricts any modeling efforts where longer trials are needed for this to be a valid tool. In chapter four's discussion, we introduced a PID control model as a possible descriptor of the changes in sensory information use and its effect on sway. It may be beneficial to conduct future studies with a smaller number of longer, continuous trials in order to utilize this model for the further investigation of the underlying mechanisms of this tuning response. Qualitative and quantitative model predictions could be compared to the collected sway trajectories. If the manipulated parameters of the PID model produced changes in the simulated sway trajectories that mimic what is seen in development it could inform our understanding of vision's role in postural control development.

In summary, the goal for future studies should include a broader range of stimulus manipulations to further characterize the children's responses to dynamic visual stimuli. If the children's responses to these extended stimulus variations show differences when compared to adults, there may be an indication of further developmental changes in the use of vision for postural control. Future studies should also incorporate modeling techniques to further investigate the tuning response seen with development. While we were able to observe the postural response tuning, the underlying mechanisms that caused these changes are still in need of further study. The PID control model introduced in Peterka (2000) is a possible candidate for this analysis based upon the hypothesis that the development of the response tuning are due to changes in the use of various properties of the sensory stimulus. These goals must be met in order to extend the knowledge base concerning the development of postural control.

APPENDIX A

PARTICIPANT CONSENT FORMS EXPERIMENT 1

PARENTAL CONSENT FORM

Project

The Effects of Vision on Postural Control in Children.

Statement of Subject's Age

I state that I am 18 years of age and that I allow my child to participate in a program of research being conducted by Dr. Jane E. Clark, University of Maryland at College Park, Department of Kinesiology.

Purpose

I understand that the purpose of this research is to examine how the information from vision influences postural control in 6-year-old children.

Procedure

The procedure involves my child, initially, to be submitted to a test of motor performance called the Movement Assessment Battery for Children, adequate for his/her age, which will last for approximately 25 minutes and that will cause little or no physical or mental stress. On a different day, to be scheduled in agreement with the parent, the child will come to the Cognitive Motor Behavior Laboratory where an experimental session will be held. He/she will stand quietly on an elevated platform while looking to a screen where moving dots or non-moving dots will be displayed. A small plastic triangle, which constitutes an ultrasound tracker, will be attached to the child's lower back and to a band on the head so that the movement of the head and body can be measured. Eight to ten trials will be collected. Each trial will last one minute. The whole experimental session will last one hour. The entire testing session will be videotaped to monitor the postural behavior during the experimental session.

Risks

I understand that as a result of my child's participation in this study, he/she may experience muscle fatigue but there are no other known risks and no long-term effect associated with participation in this study.

Confidentiality

All information about the children is confidential and the child's name will not be identified any time. All videotape material will be secured in locked cabinets in the laboratory, were only the principal investigator and lab assistants will have access to them. The tapes will be destroyed after the completion of the study.

Benefits: Freedom to Withdraw and Ask Questions

I understand that this experiment is not designed to help my child, but that the investigation seeks to learn more about postural control in children. I understand that I am free to ask questions or to withdraw my child from participation at any time without penalty. I understand that I must have signed copy of this consent form given to me and that the investigators will provide me the results from the study.

Where Medical Care is Available (as applicable)

In the event of child's physical injury resulting from participation in this study, I understand that immediate medical treatment is available nearby at Washington Adventist Hospital in Takoma Park. However, I understand that the University of Maryland does not provide any medical or hospital insurance coverage for the participants in the research study nor will the University of Maryland provide compensation for any injury sustained as a result of participation in this research study except as required by law.

Name, Address and Phone of Principal Investigator

Jane E. Clark
Department of Kinesiology, College of Health and Human Performance, UM
at College Park
(301) 405-2474 (office)
(301) 405-2574 (lab)

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Name of child	Birthday
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Signature of parent	Date

CONSENT FORM

Project	The Effects of Vision on Postural Control in Children.
Statement of Subject's Age	I state that I am 18 years of age and that I wish to participate in a program of research being conducted by Dr. Jane E. Clark, University of Maryland at College Park, Department of Kinesiology.
Purpose	I understand that the purpose of this research is to examine how the information from vision influences postural control in adults to compare to children.
Procedure	The procedure involves me to come to the Cognitive Motor Behavior Laboratory where the experimental session will be held. I will stand quietly barefoot in a heel-to-toe stance while looking to a screen where moving dots will be displayed while wearing goggles. A small plastic triangle, which constitutes an ultrasound tracker, will be attached to my lower back and to a band on the head so that the movement of the head and body can be measured. Eight to ten trials will be collected. Each trial will last one minute. The whole experimental session will last one hour. The entire testing session will be videotaped to monitor the postural behavior during the experimental session.
Risks	I understand that as a result of my participation in this study, I may experience muscle fatigue but there are no other known risks and no long-term effect associated with participation in this study.
Confidentiality	All information about my participation is confidential and my name will not be identified any time. All videotape material will be secured in locked cabinets in the laboratory, were only the principal investigator and lab assistants will have access to them. The tapes will be destroyed after the completion of the study.
Benefits: Freedom to Withdraw and Ask Questions	I understand that this experiment is not designed to help me personally, but that the investigation seeks to learn more about postural control in children. I understand that I am free to ask questions or to withdraw from participation at any time without penalty. I understand that I must have signed copy of this consent form given to me and that the investigators will provide me the results from the study.
Where Medical Care is Available (as applicable)	In the event of physical injury resulting from participation in this study, I understand that immediate medical treatment is available nearby at Washington Adventist Hospital in Takoma Park. However, I understand that the University of Maryland does not provide any medical or hospital insurance coverage for the participants in the research study nor will the University of Maryland provide compensation for any injury sustained as a result of participation in this research study except as required by law.
Name, Address and Phone of Principal Investigator	Jane E. Clark Department of Kinesiology, College of Health and Human Performance, UM at College Park (301) 405-2474 (office) (301) 405-2574 (lab)

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Name of participant Birthday

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Signature of participant Date

APPENDIX B

PARTICIPANT CONSENT FORMS FOR EXPERIMENT 2

PARENTAL CONSENT FORM

Project	The Effects of Vision on Postural Control in Children.
Statement of Subject's Age	I state that I am 18 years of age and that I wish my child to participate in a program of research being conducted by Dr. Jane E. Clark, University of Maryland at College Park, Department of Kinesiology.
Purpose	I understand that the purpose of this research is to examine how the information from vision influences postural control in children.
Procedure	The procedure involves my child to come to the Cognitive Motor Behavior Laboratory where the experimental session will be held. He/she will stand quietly, barefoot in a heel-to-toe stance on an elevated platform while looking to a screen where moving dots or non-moving dots will be displayed while wearing goggles. A small plastic triangle, which constitutes an ultrasound tracker, will be attached to the child's lower back and to a band on the head so that the movement of the head and body can be measured. Twelve 60 second trials will be collecte The whole experimental session will last approximately one and a half hours. At the end of the experimental session my child will receive stickers and a small toy.
Risks	I understand that as a result of my child's participation in this study, he/she may experience muscle fatigue but there are no other known risks and no long-term effect associated with participation in this study.
Confidentiality	All information about the children is confidential and the child's name will not be identified any time. All participant material will be secured in locked cabinets in the laboratory, were only the principal investigator and lab assistants will have access to them.
Benefits: Freedom to Withdraw and Ask Questions	I understand that this experiment is not designed to help my child, but that the investigation seeks to learn more about postural control in children. I understand that I am free to ask questions or to withdraw my child from participation at any time without penalty. I understand that I must have signed copy of this consent form given to me and that the investigators will provide me the results from the study.
Where Medical Care is Available (as applicable)	The University of Maryland does not provide any medical or hospital insurance coverage for the participants in the research study nor will the University of Maryland provide compensation for any injury sustained as a result of participation in this research study except as required by law.
Name, Address and Phone of Principal Investigator	Jane E. Clark Department of Kinesiology, College of Health and Human Performance, UM at College Park (301) 405-2474 (office) (301) 405-2574 (lab)

If you have any questions about your rights or those of your child as a research subject you may contact:

Marc Rogers, Chair
HSRC Dept. of Kinesiology
301-405-2484 email: mrogers1@umd.edu

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Name of child Birthday

Name of Parent

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Signature of Parent Date

CONSENT FORM

Project	The Effects of Vision on Postural Control in Children.
Statement of Subject's Age	I state that I am 18 years of age and that I wish to participate in a program of research being conducted by Dr. Jane E. Clark, University of Maryland at College Park, Department of Kinesiology.
Purpose	I understand that the purpose of this research is to examine how the information from vision influences postural control in adults to compare to children.
Procedure	The procedure involves me to come to the Cognitive Motor Behavior Laboratory where the experimental session will be held. I will stand quietly barefoot in a heel-to-toe stance while looking to a screen where moving dots or non-moving dots will be displayed while wearing goggles. A small plastic triangle, which constitutes an ultrasound tracker, will be attached to my lower back and to a band on the head so that the movement of the head and body can be measured. Twelve 60 second trials will be collected. The whole experimental session will last approximately one and a half hours.
Risks	I understand that as a result of my participation in this study, I may experience muscle fatigue but there are no other known risks and no long-term effect associated with participation in this study.
Confidentiality	All information about my participation is confidential and my name will not be identified any time. All participant material will be secured in locked cabinets in the laboratory, were only the principal investigator and lab assistants will have access to them.
Benefits: Freedom to Withdraw and Ask Questions	I understand that this experiment is not designed to help me personally, but that the investigation seeks to learn more about postural control in children. I understand that I am free to ask questions or to withdraw from participation at any time without penalty. I understand that I must have signed copy of this consent form given to me and that the investigators will provide me the results from the study.
Where Medical Care is Available (as applicable)	The University of Maryland does not provide any medical or hospital insurance coverage for the participants in the research study nor will the University of Maryland provide compensation for any injury sustained as a result of participation in this research study except as required by law.
Name, Address and Phone of Principal Investigator	Jane E. Clark Department of Kinesiology, College of Health and Human Performance, UM at College Park (301) 405-2474 (office) (301) 405-2574 (lab)

If you have any questions about your rights as a research subject you may contact:

Marc Rogers, Chair
HSRC Dept. of Kinesiology
301-405-2484 email: mrogers1@umd.edu

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Name of participant Birthday

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Signature of participant Date

APPENDIX C

SUMMARY OF DATA SPREADSHEETS EXPERIMENT 1

4-year-olds Mean Gain Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	0.703	0.787	0.839	1.189	1.729	1.049
2	0.715	0.692	0.750	1.036	1.560	1.783
3	0.559	1.507	0.894	1.306	2.333	0.908
4	0.742	0.601	1.020	1.190	0.914	1.497
5	0.600	0.848	1.765	2.486	3.674	4.169
6	0.389	0.410	0.532	0.884	0.856	1.000
7	0.210	0.445	0.378	0.325	0.999	0.854

6-year-olds Mean Gain Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	0.312	0.429	0.550	0.719	1.489	1.176
9	0.676	0.898	0.536	0.958	1.849	0.627
10	0.343	0.837	0.873	0.698	1.794	1.777
11	0.774	1.213	1.126	1.333	2.018	2.376
12	0.469	0.481	0.529	0.796	1.251	0.941
13	0.309	0.895	0.926	0.619	1.612	2.159
14	0.429	0.757	0.890	0.792	1.562	1.172

Adults Mean Gain Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	0.106	0.161	0.100	0.346	0.458	0.409
16	0.810	1.162	0.641	1.658	2.162	1.978
17	0.198	0.430	0.391	1.036	1.288	1.048
18	0.392	0.544	0.619	1.216	1.567	1.844
19	0.115	0.202	0.180	0.174	0.295	0.311
20	0.093	0.386	0.369	0.249	0.518	0.449
21	0.360	0.406	0.204	0.590	0.670	0.434

4-year-olds Gain Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	0.551	0.653	0.653	0.869	0.999	0.335
2	0.710	0.084	0.235	0.256	0.508	0.375
3	0.124	0.454	0.335	0.809	1.491	0.107
4	0.122	0.178	0.390	0.264	0.802	0.733
5	0.044	0.364	0.245	1.049	1.227	0.914
6	0.196	0.183	0.079	0.341	0.166	0.181
7	0.098	0.203	0.111	0.200	0.099	0.280

6-year-olds Gain Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	0.087	0.104	0.505	0.242	0.796	0.615
9	0.240	0.150	0.220	0.122	0.279	0.220
10	0.195	0.067	0.170	0.243	0.205	0.590
11	0.399	0.121	0.815	0.579	0.547	0.731
12	0.234	0.372	0.214	0.330	0.901	0.197
13	0.082	0.284	0.351	0.451	0.307	0.684
14	0.375	0.581	0.211	0.214	0.983	0.541

Adults Gain Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	0.008	0.026	0.079	0.061	0.072	0.193
16	0.069	0.188	0.215	0.237	0.160	0.319
17	0.077	0.158	0.107	0.712	0.574	1.002
18	0.007	0.037	0.015	0.160	0.023	0.073
19	0.006	0.109	0.099	0.045	0.197	0.199
20	0.045	0.231	0.427	0.129	0.201	0.491
21	0.127	0.266	0.010	0.182	0.426	0.055

4-year-olds Mean Phase Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	126.735	39.645	71.848	166.792	-91.482	-123.567
2	91.399	16.431	-77.293	66.397	-16.314	-100.242
3	122.451	-49.641	-58.141	122.953	-48.604	-101.614
4	51.533	-83.371	-49.754	63.201	-61.681	-86.080
5	72.941	-7.543	-8.358	60.902	-13.413	-90.740
6	50.865	5.446	-70.036	30.886	-46.710	-51.115
7	125.650	-5.557	-40.937	49.255	-25.377	-102.531

6-year-olds Mean Phase Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	37.589	12.887	-25.096	32.226	-29.464	-142.401
9	56.837	-25.774	-96.881	34.429	-41.757	-92.821
10	98.189	-4.074	-45.041	63.023	-18.114	-93.739
11	64.316	3.423	-74.965	74.663	-27.555	-95.580
12	39.409	2.261	-70.845	14.309	-34.939	-88.829
13	87.764	12.471	-48.900	36.778	-0.252	-80.098
14	132.216	7.087	-89.536	101.418	24.502	-73.180

Adults Mean Phase Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	161.326	-105.266	140.261	-3.075	66.781	-6.878
16	54.365	-17.824	-63.146	30.276	-43.930	-120.731
17	-59.427	166.770	96.721	-158.978	110.560	54.556
18	-144.754	157.764	82.532	26.345	-23.866	-101.392
19	153.298	80.946	50.701	143.147	69.414	46.958
20	132.413	-156.955	43.931	136.771	-163.575	34.984
21	8.129	10.861	-32.855	10.383	4.739	-36.418

4-year-olds Phase Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	64.002	71.911	64.519	57.370	62.745	53.590
2	25.705	35.627	32.053	21.042	13.759	22.073
3	22.059	53.968	2.583	11.867	53.359	45.412
4	57.170	25.392	39.969	63.918	74.471	24.121
5	14.682	17.771	9.786	11.918	11.611	7.831
6	27.447	26.399	66.104	45.113	9.620	29.846
7	49.279	27.711	36.610	63.453	23.400	33.329

6-year-olds Phase Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	18.145	11.529	72.859	22.004	24.465	58.241
9	11.626	33.126	24.967	9.110	24.362	5.955
10	15.710	13.417	25.075	8.950	13.870	5.413
11	2.892	13.087	69.421	31.964	14.671	21.068
12	16.991	21.597	6.394	12.690	44.570	30.117
13	23.009	7.004	16.247	10.175	9.509	17.796
14	50.931	41.754	39.466	24.541	59.945	50.223

Adults Phase Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	16.187	18.610	44.963	22.644	16.748	19.717
16	12.500	7.763	9.015	13.204	7.054	18.041
17	44.312	44.286	12.209	54.419	25.093	36.274
18	6.142	4.472	7.126	2.844	1.941	7.710
19	52.300	69.818	22.136	59.439	70.614	8.384
20	58.794	62.926	64.764	66.908	63.525	63.564
21	64.572	47.382	39.573	65.160	37.749	40.920

4-year-olds Mean residsway Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	0.229	0.170	0.182	0.376	0.309	0.250
2	0.283	0.102	0.128	0.248	0.188	0.220
3	0.235	0.178	0.209	0.367	0.298	0.314
4	0.242	0.224	0.269	0.442	0.445	0.433
5	0.210	0.162	0.187	0.521	0.356	0.438
6	0.106	0.071	0.075	0.207	0.136	0.180
7	0.091	0.100	0.079	0.213	0.210	0.128

6-year-olds Mean residsway Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	0.122	0.094	0.087	0.221	0.195	0.146
9	0.145	0.143	0.081	0.228	0.235	0.153
10	0.098	0.070	0.074	0.181	0.135	0.142
11	0.160	0.104	0.134	0.263	0.227	0.235
12	0.136	0.112	0.098	0.204	0.194	0.162
13	0.117	0.091	0.081	0.195	0.152	0.174
14	0.206	0.194	0.148	0.365	0.267	0.222

Adults Mean residsway Values

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	0.031	0.027	0.024	0.087	0.072	0.070
16	0.075	0.063	0.059	0.133	0.113	0.105
17	0.089	0.066	0.067	0.263	0.173	0.223
18	0.044	0.030	0.032	0.121	0.086	0.082
19	0.073	0.057	0.053	0.103	0.083	0.074
20	0.078	0.081	0.074	0.132	0.112	0.106
21	0.066	0.054	0.055	0.098	0.085	0.097

4-year-olds residsway Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
1	0.049	0.036	0.032	0.121	0.099	0.024
2	0.275	0.012	0.035	0.080	0.028	0.066
3	0.006	0.063	0.070	0.192	0.066	0.098
4	0.034	0.031	0.176	0.021	0.069	0.132
5	0.056	0.045	0.037	0.164	0.026	0.050
6	0.022	0.012	0.012	0.056	0.026	0.063
7	0.013	0.026	0.011	0.025	0.061	0.031

6-year-olds residsway Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
8	0.059	0.032	0.037	0.059	0.089	0.044
9	0.027	0.049	0.012	0.046	0.040	0.046
10	0.028	0.006	0.007	0.033	0.008	0.017
11	0.056	0.015	0.015	0.147	0.059	0.032
12	0.063	0.020	0.011	0.092	0.095	0.048
13	0.021	0.016	0.003	0.056	0.031	0.013
14	0.106	0.182	0.039	0.179	0.149	0.053

Adults residsway Standard Deviation

participant	CoM 0.1Hz	CoM 0.3Hz	CoM 0.5Hz	Head 0.1Hz	Head 0.3Hz	Head 0.5Hz
15	0.002	0.001	0.005	0.009	0.002	0.020
16	0.016	0.009	0.008	0.029	0.023	0.010
17	0.020	0.013	0.014	0.034	0.062	0.128
18	0.005	0.003	0.005	0.012	0.010	0.013
19	0.008	0.011	0.007	0.011	0.021	0.016
20	0.005	0.033	0.011	0.017	0.027	0.019
21	0.010	0.010	0.008	0.010	0.006	0.030

APPENDIX D

SUMMARY OF DATA SPREADSHEETS EXPERIMENT 2

4-year-olds Mean Gain Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
1	2.313	2.598	2.310	1.556	0.737	1.241
2	3.366	1.629	2.359	2.571	1.082	1.562
3	4.212	2.630	1.907	3.474	1.348	1.034
4	4.580	2.449	1.466	3.630	1.289	1.276
5	2.421	1.082	1.573	1.539	0.519	0.671
6	3.734	3.155	2.571	2.619	1.279	0.823
7	0.917	0.961	0.268	0.812	0.350	0.275
8	6.001	1.817	1.083	5.508	1.168	1.464
9	6.914	2.292	1.889	3.898	1.035	0.708
10	4.020	2.100	1.158	2.370	1.186	0.713

6-year-olds Mean Gain Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
11	5.062	5.484	3.136	1.596	1.214	1.118
12	2.948	1.703	2.013	1.066	1.045	0.939
13	2.362	4.540	2.130	1.290	1.256	0.773
14	3.417	2.668	2.115	2.500	1.686	1.523
15	2.447	1.850	2.000	1.090	0.769	0.733
16	2.744	2.681	1.987	1.709	1.322	0.974
17	2.408	3.180	2.378	1.227	1.396	1.078
18	3.299	3.696	2.930	0.608	1.159	0.735
19	1.966	1.923	1.161	1.042	0.992	0.525
20	2.152	1.802	1.254	1.607	0.773	0.829

Adults Mean Gain Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
21	2.829	2.257	1.799	1.704	1.402	1.102
22	2.979	2.409	1.973	1.773	1.608	1.278
23	2.364	2.218	1.771	1.600	1.282	1.070
24	2.170	2.019	1.513	1.361	1.250	0.806
25	3.813	1.461	1.319	1.211	1.046	0.556
26	1.206	1.240	0.631	0.852	0.893	0.410
27	1.943	1.854	1.786	1.491	1.471	1.422
28	1.830	1.423	0.797	1.157	0.953	0.419
29	2.868	2.717	2.262	1.692	1.330	0.836
30	2.959	2.307	2.526	1.908	1.422	1.445

4-year-olds Gain Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
1	0.270	1.516	0.698	1.364	0.190	0.507
2	0.245	0.230	0.259	0.678	0.177	0.139
3	0.439	0.630	0.527	2.557	0.216	0.239
4	2.631	0.743	0.050	1.602	0.736	0.245
5	3.280	1.452	0.755	1.625	0.614	0.308
6	0.304	0.251	0.925	0.425	0.356	0.519
7	0.734	1.118	0.211	0.465	0.262	0.205
8	3.757	0.642	0.984	0.608	0.399	0.509
9	0.062	1.096	0.638	3.751	0.717	0.364
10	2.953	0.639	0.513	1.811	0.498	0.112

6-year-olds Gain Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
11	1.132	0.551	0.365	0.300	0.113	0.240
12	4.139	4.012	0.805	0.832	0.247	0.091
13	0.297	1.552	0.545	0.454	0.756	0.164
14	1.362	0.173	0.218	0.560	0.276	0.130
15	1.581	1.387	0.268	0.751	0.583	0.330
16	1.851	1.000	0.369	0.485	0.310	0.326
17	2.457	0.702	1.209	0.160	0.748	0.445
18	0.271	0.635	0.512	1.102	0.304	0.112
19	0.252	0.588	0.411	0.119	0.121	0.224
20	0.253	0.199	0.386	0.251	0.428	0.212

Adults Gain Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
21	0.312	0.261	0.111	0.449	0.067	0.096
22	0.610	0.355	0.142	0.530	0.230	0.141
23	0.230	0.245	0.137	0.280	0.258	0.084
24	0.749	0.084	0.138	0.449	0.127	0.017
25	0.610	0.414	0.129	0.347	0.337	0.147
26	1.772	0.912	1.091	0.119	0.474	0.190
27	0.026	0.149	0.223	0.146	0.156	0.105
28	1.051	0.179	0.206	0.734	0.050	0.192
29	0.534	0.114	0.467	0.267	0.252	0.206
30	0.263	0.108	0.785	0.215	0.138	0.076

4-year-olds Mean SFSA Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
1	0.289	0.227	0.636	0.905	0.141	0.153	0.180	0.486
2	0.295	0.330	0.399	0.924	0.202	0.252	0.265	0.612
3	0.683	0.413	0.644	0.747	0.461	0.341	0.330	0.405
4	0.311	0.450	0.600	0.575	0.264	0.356	0.316	0.500
5	0.184	0.238	0.265	0.617	0.124	0.151	0.127	0.263
6	0.415	0.261	0.555	0.723	0.264	0.183	0.226	0.232
7	0.065	0.090	0.235	0.105	0.028	0.080	0.086	0.108
8	0.122	0.420	0.321	0.304	0.236	0.389	0.206	0.410
9	0.597	0.678	0.561	0.740	0.295	0.383	0.253	0.277
10	0.207	0.394	0.514	0.454	0.132	0.232	0.290	0.279

6-year-olds Mean SFSA Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
11	0.284	0.497	1.343	1.229	0.205	0.157	0.297	0.438
12	0.214	0.289	0.417	0.789	0.140	0.105	0.256	0.368
13	0.195	0.232	1.111	0.834	0.082	0.127	0.307	0.303
14	0.198	0.335	0.653	0.730	0.229	0.245	0.413	0.507
15	0.115	0.240	0.453	0.784	0.046	0.107	0.188	0.287
16	0.186	0.269	0.656	0.779	0.065	0.168	0.324	0.382
17	0.202	0.236	0.779	0.932	0.067	0.120	0.342	0.422
18	0.299	0.324	0.905	1.148	0.141	0.060	0.284	0.288
19	0.121	0.193	0.471	0.455	0.040	0.102	0.243	0.206
20	0.072	0.211	0.441	0.491	0.046	0.158	0.189	0.325

Adults Mean SFSA Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
21	0.073	0.278	0.553	0.705	0.058	0.167	0.343	0.432
22	0.128	0.292	0.590	0.773	0.075	0.174	0.394	0.501
23	0.078	0.232	0.543	0.694	0.050	0.157	0.314	0.419
24	0.060	0.213	0.494	0.593	0.045	0.133	0.306	0.316
25	0.202	0.374	0.358	0.517	0.191	0.119	0.256	0.218
26	0.041	0.118	0.304	0.247	0.042	0.084	0.219	0.161
27	0.175	0.191	0.454	0.700	0.130	0.146	0.360	0.557
28	0.044	0.180	0.349	0.313	0.032	0.114	0.233	0.164
29	0.068	0.281	0.665	0.887	0.028	0.166	0.326	0.328
30	0.114	0.290	0.565	0.990	0.066	0.187	0.348	0.566

4-year-olds SFSA Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
1	0.232	0.027	0.371	0.274	0.069	0.134	0.046	0.199
2	0.104	0.024	0.056	0.102	0.087	0.067	0.043	0.055
3	0.425	0.043	0.154	0.206	0.417	0.251	0.053	0.094
4	0.209	0.258	0.182	0.020	0.097	0.157	0.180	0.096
5	0.148	0.229	0.254	0.213	0.070	0.113	0.109	0.088
6	0.129	0.030	0.061	0.363	0.143	0.042	0.087	0.203
7	0.030	0.072	0.273	0.083	0.019	0.046	0.064	0.080
8	0.580	0.369	0.157	0.386	0.199	0.060	0.098	0.200
9	0.051	0.008	0.193	0.180	0.093	0.266	0.126	0.104
10	0.113	0.290	0.156	0.201	0.104	0.178	0.122	0.044

6-year-olds SFSA Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
11	0.063	0.111	0.135	0.143	0.030	0.029	0.028	0.094
12	0.114	0.406	0.982	0.316	0.143	0.082	0.060	0.036
13	0.041	0.029	0.379	0.213	0.030	0.045	0.185	0.064
14	0.062	0.134	0.042	0.085	0.011	0.055	0.068	0.051
15	0.029	0.155	0.340	0.229	0.099	0.074	0.143	0.087
16	0.140	0.182	0.245	0.145	0.021	0.048	0.076	0.128
17	0.121	0.241	0.172	0.474	0.084	0.016	0.183	0.175
18	0.019	0.027	0.155	0.200	0.039	0.108	0.074	0.044
19	0.053	0.025	0.144	0.161	0.022	0.012	0.030	0.088
20	0.063	0.025	0.049	0.151	0.016	0.025	0.105	0.083

Adults SFSA Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
21	0.136	0.031	0.064	0.044	0.075	0.044	0.016	0.038
22	0.029	0.060	0.087	0.056	0.033	0.052	0.056	0.055
23	0.022	0.022	0.060	0.054	0.002	0.027	0.063	0.033
24	0.067	0.073	0.021	0.054	0.035	0.044	0.031	0.007
25	0.015	0.060	0.101	0.051	0.023	0.034	0.082	0.058
26	0.018	0.174	0.223	0.428	0.026	0.012	0.116	0.074
27	0.022	0.003	0.037	0.087	0.011	0.014	0.038	0.041
28	0.088	0.103	0.044	0.081	0.060	0.072	0.012	0.075
29	0.067	0.052	0.028	0.183	0.047	0.026	0.062	0.081
30	0.026	0.026	0.026	0.308	0.022	0.021	0.034	0.030

4-year-olds Mean Phase Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
1	39.781	-35.869	-33.924	91.687	-28.892	-28.380
2	-15.239	-60.844	-12.186	-27.883	-47.818	-7.311
3	114.129	-25.027	-3.595	99.618	-18.324	53.022
4	-7.582	-14.840	-35.046	-33.634	8.530	-5.237
5	-40.946	-13.562	-43.063	-36.006	18.073	-32.778
6	-16.340	-49.542	-21.143	2.476	3.960	21.151
7	-7.436	8.523	5.026	-17.445	25.672	-41.047
8	61.792	-38.783	-53.181	-9.483	-44.810	46.049
9	-19.291	152.481	-25.128	-75.883	92.930	-37.608
10	-45.334	113.056	-55.646	-30.459	103.049	1.047

6-year-olds Mean Phase Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
11	-20.235	-37.256	-29.173	-19.399	-18.667	-15.141
12	-82.471	-35.258	-40.341	-93.280	-8.981	-14.934
13	-64.724	-34.506	-31.862	-44.863	-2.131	-6.243
14	-14.175	-18.737	-26.507	-28.462	1.166	15.113
15	-66.665	-30.338	-28.470	-79.933	-9.581	-17.885
16	-18.286	-36.583	-28.993	-42.398	-8.764	15.797
17	19.722	-42.233	-26.544	-11.091	5.804	47.228
18	2.897	-32.501	-19.763	-42.735	-15.317	13.372
19	-20.674	-12.841	2.914	-1.873	15.869	21.303
20	-24.353	-24.196	-12.194	-12.230	13.374	3.791

Adults Mean Phase Values

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
21	-44.093	-25.809	-28.456	-43.631	-25.145	-26.639
22	-21.737	-16.691	-15.144	-21.455	-9.220	-9.760
23	-32.288	-22.983	-10.483	-14.812	-17.413	0.442
24	-25.201	-27.718	-22.731	-17.745	-15.778	-9.216
25	-17.439	-13.803	9.166	-17.929	-12.426	19.738
26	-74.796	-45.515	-12.765	-60.942	32.843	26.381
27	-52.956	-39.502	-5.834	-58.936	-38.328	1.373
28	0.596	-16.036	-7.867	5.355	-10.947	-3.080
29	-38.241	-39.933	-36.167	-24.522	-29.849	-16.661
30	-39.665	-30.039	-22.967	-30.634	-13.182	0.538

4-year-olds Phase Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
1	38.446	23.496	5.760	56.148	20.533	37.734
2	50.420	32.000	8.904	66.165	17.845	10.353
3	53.031	16.747	14.009	56.454	22.523	52.096
4	54.415	45.376	47.845	12.783	67.993	51.071
5	38.476	21.662	2.305	57.992	52.620	28.089
6	30.242	35.251	7.350	38.159	66.041	5.516
7	33.179	48.043	45.491	28.604	41.700	41.358
8	55.574	61.510	72.744	24.764	12.229	67.937
9	68.942	76.555	63.318	64.332	69.449	25.734
10	19.942	67.764	60.423	46.408	69.169	19.007

6-year-olds Phase Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
11	33.080	2.738	6.869	42.820	9.942	8.418
12	27.840	6.495	14.875	47.729	14.444	3.709
13	31.405	14.645	18.895	29.976	41.873	17.100
14	33.143	1.895	8.444	41.781	3.834	8.733
15	18.432	10.617	7.845	40.316	16.687	2.568
16	36.951	12.360	25.970	26.847	26.222	17.973
17	64.326	8.568	13.924	73.982	19.838	34.320
18	25.564	4.399	8.773	38.916	5.277	21.452
19	21.170	13.977	21.116	17.292	6.316	22.147
20	16.666	6.592	7.775	34.893	21.190	11.634

Adults Phase Standard Deviation

participant	Head 2mm	Head 5mm	Head 8mm	CoM 2mm	CoM 5mm	CoM 8mm
21	24.167	0.825	4.721	24.631	4.182	3.617
22	5.011	4.296	13.080	6.251	7.203	10.560
23	7.781	5.385	9.040	15.545	5.395	7.066
24	5.407	1.309	3.654	14.189	1.247	1.314
25	13.193	10.428	27.546	12.078	10.054	27.005
26	54.314	44.466	30.277	61.137	65.385	34.557
27	4.062	2.432	6.313	7.139	3.128	10.146
28	51.121	13.803	1.792	53.211	13.180	0.591
29	8.990	7.178	5.322	10.980	12.013	4.827
30	4.509	5.874	3.404	7.604	1.812	3.336

4-year-olds Mean residsway Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
1	0.389	0.414	0.317	0.402	0.219	0.308	0.174	0.266
2	0.322	0.208	0.188	0.239	0.219	0.174	0.130	0.178
3	0.579	0.343	0.271	0.329	0.612	0.218	0.182	0.226
4	0.416	0.352	0.410	0.329	0.333	0.265	0.235	0.236
5	0.306	0.285	0.272	0.267	0.233	0.191	0.169	0.171
6	0.370	0.194	0.323	0.370	0.195	0.114	0.224	0.165
7	0.078	0.077	0.117	0.097	0.054	0.059	0.085	0.063
8	0.248	0.325	0.356	0.254	0.310	0.351	0.358	0.345
9	0.793	0.803	0.659	0.663	0.383	0.396	0.347	0.318
10	0.381	0.447	0.451	0.373	0.234	0.294	0.306	0.227

6-year-olds Mean residsway Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
11	0.391	0.400	0.444	0.299	0.193	0.166	0.194	0.124
12	0.241	0.209	0.214	0.177	0.156	0.117	0.126	0.099
13	0.206	0.236	0.466	0.239	0.090	0.114	0.204	0.112
14	0.243	0.206	0.234	0.148	0.165	0.133	0.129	0.113
15	0.141	0.174	0.107	0.131	0.069	0.088	0.056	0.074
16	0.185	0.268	0.299	0.242	0.122	0.157	0.190	0.167
17	0.214	0.247	0.176	0.224	0.090	0.131	0.088	0.118
18	0.240	0.277	0.412	0.278	0.117	0.118	0.180	0.111
19	0.110	0.104	0.171	0.134	0.064	0.063	0.088	0.074
20	0.082	0.083	0.140	0.116	0.053	0.069	0.077	0.085

Adults Mean residsway Values

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
21	0.067	0.080	0.076	0.081	0.041	0.047	0.045	0.043
22	0.129	0.100	0.100	0.107	0.065	0.061	0.062	0.063
23	0.068	0.069	0.076	0.089	0.040	0.054	0.045	0.043
24	0.084	0.063	0.068	0.080	0.054	0.043	0.047	0.046
25	0.183	0.207	0.184	0.265	0.115	0.122	0.105	0.140
26	0.060	0.055	0.066	0.077	0.053	0.044	0.050	0.051
27	0.137	0.118	0.093	0.128	0.075	0.092	0.068	0.091
28	0.072	0.056	0.080	0.098	0.048	0.038	0.052	0.063
29	0.091	0.075	0.100	0.133	0.047	0.037	0.040	0.048
30	0.141	0.115	0.114	0.153	0.083	0.074	0.062	0.097

4-year-olds residsway Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
1	0.266	0.068	0.092	0.176	0.111	0.071	0.041	0.076
2	0.106	0.081	0.092	0.064	0.075	0.063	0.056	0.067
3	0.254	0.059	0.028	0.055	0.169	0.110	0.079	0.133
4	0.059	0.135	0.117	0.062	0.021	0.100	0.082	0.059
5	0.148	0.229	0.254	0.213	0.070	0.113	0.109	0.088
6	0.082	0.080	0.039	0.059	0.122	0.119	0.030	0.066
7	0.014	0.005	0.082	0.026	0.001	0.009	0.047	0.009
8	0.008	0.189	0.104	0.285	0.066	0.060	0.154	0.043
9	0.022	0.113	0.047	0.098	0.020	0.125	0.099	0.034
10	0.049	0.008	0.041	0.060	0.052	0.053	0.109	0.004

6-year-olds residsway Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
11	0.050	0.038	0.037	0.055	0.013	0.011	0.028	0.024
12	0.180	0.153	0.155	0.118	0.072	0.031	0.098	0.035
13	0.037	0.057	0.246	0.013	0.011	0.019	0.103	0.007
14	0.007	0.077	0.023	0.047	0.008	0.050	0.003	0.005
15	0.093	0.041	0.103	0.044	0.086	0.037	0.056	0.015
16	0.073	0.116	0.037	0.020	0.009	0.074	0.015	0.041
17	0.068	0.179	0.212	0.108	0.007	0.055	0.079	0.031
18	0.045	0.075	0.006	0.111	0.031	0.048	0.028	0.083
19	0.007	0.012	0.062	0.014	0.001	0.006	0.015	0.031
20	0.020	0.026	0.092	0.046	0.011	0.018	0.054	0.035

Adults residsway Standard Deviation

participant	Head static	Head 2mm	Head 5mm	Head 8mm	CoM static	CoM 2mm	CoM 5mm	CoM 8mm
21	0.103	0.009	0.016	0.007	0.035	0.014	0.013	0.008
22	0.010	0.005	0.011	0.021	0.008	0.003	0.003	0.010
23	0.005	0.005	0.012	0.012	0.002	0.002	0.005	0.001
24	0.012	0.008	0.018	0.036	0.006	0.015	0.006	0.005
25	0.015	0.003	0.007	0.031	0.009	0.009	0.012	0.017
26	0.027	0.044	0.040	0.175	0.011	0.008	0.036	0.041
27	0.022	0.010	0.011	0.033	0.013	0.005	0.008	0.025
28	0.047	0.008	0.015	0.022	0.025	0.010	0.014	0.023
29	0.022	0.018	0.045	0.063	0.024	0.024	0.012	0.062
30	0.015	0.010	0.030	0.040	0.007	0.004	0.005	0.007

Reference List

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