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Development of visually driven postural reactivity: A fully immersive virtual reality study

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The objective of this study was to investigate the development of visually driven postural regulation in typically developing children of different ages. Thirty-two typically developing participants from 5 age groups (5–7 years, 8–11 years, 12–15 years, 16–19 years, or 20–25 years) were asked to stand within a virtual tunnel that oscillated in an anterior–posterior fashion at three different frequencies (0.125, 0.25, and 0.5 Hz). Body sway (BS) and postural perturbations (as measured by velocity root mean squared or vRMS) were measured. Most of the 5- to 7-year-old participants (67%) were unable to remain standing during the dynamic conditions. For older participants, BS decreased significantly with age for all frequencies. Moreover, vRMS decreased significantly from the 8- to 11- through 16- to 19-years age groups (greatest decreases for 0.5 Hz, followed by 0.25-Hz and 0.125-Hz conditions). No difference of frequency or instability was found between the 16- to 19- and 20- to 25-year-old groups for most conditions. Results suggest an over-reliance on visual input relative to proprioceptive and vestibular inputs on postural regulation at young ages (5–7 years). The finding that vRMS decreased significantly with age before stabilizing between 16 and 19 years suggests an important transitory period for sensorimotor development within this age range.

Keywords: posture, sensorimotor development, virtual environment, body sway, instability index

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Introduction

Humans use three different afferent sensory systems to regulate their posture; the somatosensory, the vestibular, and the visual systems (Nolan, Grigorenko, & Thorstensson, 2005; Peterka & Benolken, 1995). Numerous studies have shown that children rely more heavily on the visual system to regulate their posture than do adults (Foster, Sveistrup, & Woollacott, 1996; Grasso, Assaiante, Prévost, & Berthoz, 1988; Hirabayashi & Iwasaki, 1995; Minshew, Sung, Jones, & Furman, 2004; Peterka & Black, 1990; Riach & Hayes, 1987; Shumway-Cook & Woollacott, 1985; Sparto et al., 2006) suggesting that these sensory systems operate differentially during childhood (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985).

The classical Lee and Aronson's (1974) swinging-room paradigm has been used by several researchers to investigate the development of postural reactivity. Although it has proven to be an efficient and ecologically valid method to induce postural reactivity, this paradigm does not allow for a precise control over variables defining the visual stimulation (i.e., oscillation frequency) in addition to inaccurate measurement of body movement as a function of stimulation. Moreover, the studies mentioned above have not assessed a large enough age range to assess transitory developmental phases. The present study was intended to assess the major transitory developmental phases of visuo-motor integration from the ages of 5 to 25 years using a fully immersive virtual reality environment.

Riach and Hayes (1987) demonstrated that postural sway decreases linearly with age, with children using visual information to control balance differently from adults until adult-like balance-control strategies begin to appear at 7 to 8 years. Similarly, other studies have demonstrated that younger children manifest a stronger dependence on visual input for postural control (Grasso

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et al., 1998; Shumway-Cook & Woollacott, 1985), where a shift away from visual control is evidenced by 7 to 8 years of age (Assaiante & Amblard, 1993; Hay, Fleury, Bard, & Teasdale, 1994). However, other studies suggest that adult-like visual postural control develops at an older age. For example, Hirabayashi and Iwasaki (1995) argue that children do not demonstrate adult-level postural control until they reach 14 years of age. Regardless of the divergent findings regarding the age of visuo-motor maturation, it is widely accepted that as children grow older and develop, the over-reliance on the visual system to regulate posture decreases (i.e., Foster et al., 1996; Minshew et al., 2004).

Evidence suggests that differences in postural control between children and adults are only detectable when the inducing environment is dynamic, and not when it is static. This phenomenon was highlighted in a study by Peterka and Black (1990) in which the postural control (measured by postural sway) of participants ranging from 7 to 80 years of age was assessed. When presented with a static visual scene, no age-related increases in postural sway were found for participants standing on a fixed support surface with eyes either opened or closed. However, age-related increases in sway were found only for conditions involving transient information. Therefore, stimuli consisting of a dynamic information (i.e., optic flow) are ideal when assessing the role of vision in postural control. In addition, peripheral flow stimuli, i.e., dynamic stimulation presented laterally relative to eyes fixating the horizon, induce a greater amount of sway compared to central flow stimulation, i.e., dynamic stimulation presented near fixation (Slobounov et al., 2006; Stoffregen, Schmuckler, & Gibson, 1987).

Lee, Cheng, and Lin (2004) have developed a balance assessment system in which the visual stimulus is generated by a virtual reality (VR) technique where somatosensation is obtained using a movable platform. Their system demonstrated the feasibility of using a VR environment in postural control trials because of their success in inducing postural reactions with the stimuli that provided more realistic visual inputs. Moreover, Sparto et al. (2006) also used a VR system that consisted of a room where the peripheral scene (the two lateral walls) was composed of a checkerboard pattern that moved simultaneously with a central scene (which consisted of black and white concentric circles that expanded and contracted at different frequencies). This system was immersive and aimed at reproducing the effects of the swinging room paradigm and it proved to be an efficient method for inducing postural reactivity. Although Sparto et al.'s experimental paradigm and setup were efficient, they only assessed children from 7 to 12 years of age. All children were assigned to a single group: "Children." No effect of age was investigated within that group; hence, they may have missed transitory phases of development if they occurred outside of the tested range or even within this range.

The goal of our study was to attempt to improve on previous studies by assessing the development of postural reactivity of participants whose ages subtend a large range; from early school-aged children (from 5 to 7 years) through early adulthood (adults aged from 20 to 25 years). A fully immersive VR environment was used to present participants with a virtual tunnel (providing a peripheral flow stimulus) that oscillated at three different frequencies. Postural reactivity was measured using two variables: Body Sway or BS (the anterior–posterior displacement of a person as a function of the oscillation frequency; see Faubert & Allard, 2004; Lee & Aronson, 1974; Minshew et al., 2004; Schmuckler, 1997; Sparto et al., 2006) and velocity root mean squared or vRMS (antero-posterior, lateral and vertical displacement during stimulation; see Faubert & Allard, 2004). These two measures reflect distinct visuo-motor behaviors. The BS measure represents a frequency-specific body sway, which is the antero-posterior displacement in degrees of a person at the frequency of the stimulus, reflecting the observer's capacity to react to, and synchronize with a given stimulus of a certain magnitude. The vRMS is a measure of velocity in cm/s obtained for all frequencies except that of the stimulus; this measure indicates the total displacements of a person as a function of time that is not directly driven by the frequency of the visual stimulus, therefore reflecting the observer's overall postural perturbations during exposure to visual information.

It is hypothesized that the younger participants will demonstrate a higher amount of BS compared to the adult participants since children seem to rely more heavily on visual input for postural control than adults do (Foster et al., 1996; Schmuckler, 1997; Sparto et al., 2006). Furthermore, it is hypothesized that the amount of BS will decrease as the age increases. Regarding the vRMS measure, it is hypothesized that children would show greater vRMS measures compared to adults. In essence, postural stability is expected to increase with age. Finally no differences in stability are expected between children and adults groups during the static environment conditions (Peterka & Black, 1990).

Methods

Participants

Thirty-two typically developing participants (16 females and 16 males) with no history of psychiatric treatment, learning disabilities, mood disorders, or problems with audition voluntarily participated in this study. All participants had normal or corrected-to-normal vision (20/20 Snellen acuity for both eyes) and were not taking medication when they participated. Participants were categorized according to 5 age groups: 5–7 years

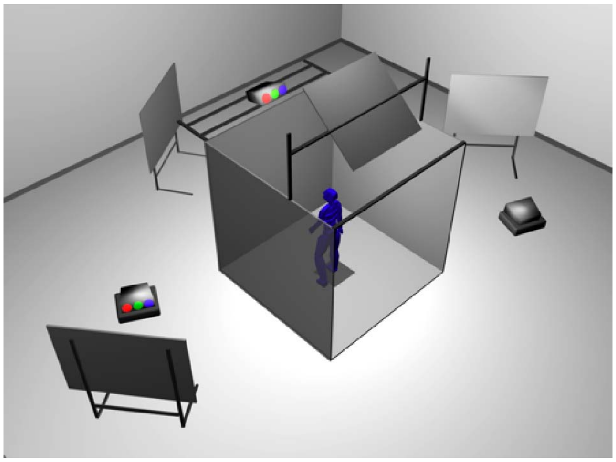

Figure 1. The CAVE is an 8 × 8 × 8 foot room that includes three walls (one frontal and two lateral) and a floor that all serve as surfaces for image projection.

($n = 6$), 8–10 years ($n = 7$), 11–14 years ($n = 6$), 15–19 years ($n = 6$), and 20–25 years ($n = 7$). The 20- to 25-years group was considered the adult group.

Apparatus

Postural reactivity to visual information was assessed using a fully immersive virtual environment or the CAVE system (Fakespace™). The CAVE is an 8 × 8 × 8 feet room that includes three canvas walls (one frontal and two laterals) and an epoxy floor that all serve as surfaces for image projection (Figure 1). The resolution of each surface image was 1280 × 1024 pixels and was generated by Marquee Ultra 8500 projectors. The CAVE is under the control of a SGI ONYX 3200 computer (with two Infinite Reality II graphics cards) and is equipped with a magnetic motion tracker system (Flock-of-Birds) capable of measuring postural reactivity by registering body movement. A magnetic motion sensor was located on stereoscopic goggles polarized at 90° (Crystal Eyes) from the StereoGraphics Corporation. For more information on our CAVE system and its provider companies, please visit the following Web site: http://vision.opto.umontreal.ca.

Procedure

After their visual acuity was evaluated using a Snellen eye-chart, participants were familiarized with the virtual environment. They were then asked to wear the stereoscopic goggles, which allowed them to perceive the 3D characteristic of the environment and for the precise tracking of their motion with the magnetic sensors. Each participant was then positioned 1.50 m from the CAVE's central wall with their shoes off, feet together, and arms crossed. This position was chosen to minimize the use of individual strategies from the limbs to maintain posture and help maximize the effect of the stimulation. For all conditions, they were asked to fixate a red dot located at the horizon. It is important to note that the tasks were passive in that behavioral information was recorded as the participants simply stood in the virtual reality environment while they were presented with the visual stimulation.

Experimental paradigm

The postural reactivity of participants was assessed using the *Virtual Tunnel Paradigm*. The tunnel had an inner texture made of a checkerboard pattern where each square was scaled for linear perspective and was 1 m^2 in dimension (Figure 2). The white squares had a luminance of 47 cd/m^2 and the black squares 0.52 cd/m^2 (98% Michelson contrast). The tunnel's virtual length was 20 m and its diameter 3 m; both of these dimensions remained constant across all trials.

The movement of the tunnel was defined by an anterior–posterior (front-back) sinusoidal translation motion oscillating with the following function: $A = 2\sin(2 \times \text{pi} \times f \times t)$, where A represents amplitude,

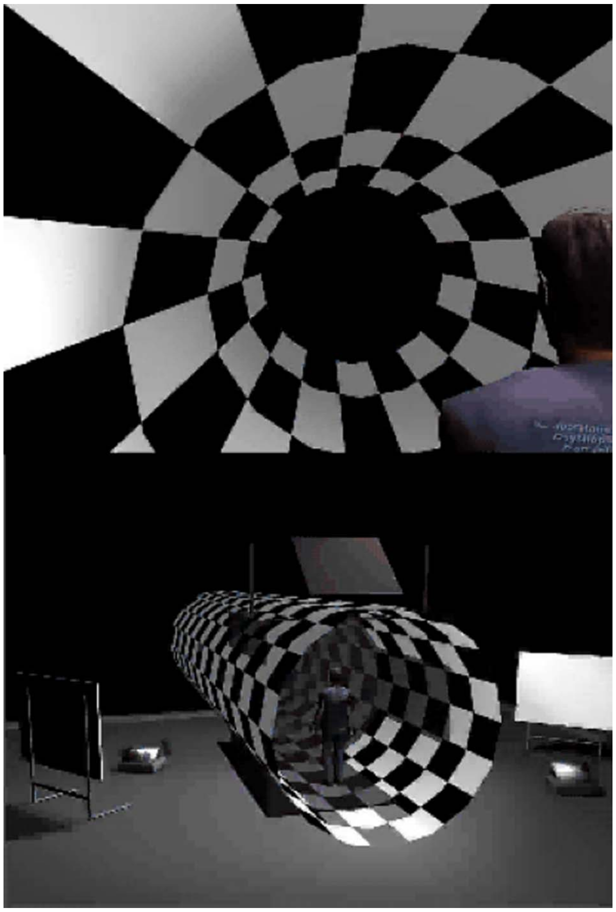

Figure 2. The Virtual Tunnel Paradigm. For demos, go to http://vision.opto.umontreal.ca.

t represents time in seconds, and f represents frequency (either 0.125 Hz (T = 8 s), 0.25 Hz (T = 4 s), or 0.5 Hz (T = 2 s)). These frequencies were chosen because low frequency translations (less than 0.40 Hz) of VR visual scenes induce the most effects with regards to postural sway (Keshner & Kenyon, 2004). As shown in the aforementioned formula, the tunnel's translation was of 2 m in amplitude at all times during dynamic trials (therefore a peak-to-peak amplitude of 4 m). Two types of conditions were used in this study: dynamic tunnel conditions and control conditions. In the dynamic tunnel conditions, the tunnel moved at the 3 different frequencies: 0.125 Hz, 0.25 Hz, or 0.5 Hz. For each frequency condition, participants performed 3 trials of 68 s each. The 9 trials were presented in a pseudo-random order where the initial frequency was randomly selected. The limiting condition was that a given frequency was never presented again until the two other frequencies were. The inter-trial interval was 5 s. However, the younger children (5- to 7-year-olds) were able to rest (if needed) after three dynamic trials since for this age group, the 9 dynamic trials were divided into 3 separate testing sessions.

The two control conditions were *static tunnel* and *eyes closed*. These conditions were added in order to isolate the contribution of dynamic optic flow to postural reactivity from that due to spontaneous sway and postural instability. In the *static tunnel* condition, participants performed two 68 s trials where they had to fixate the red dot at the horizon while presented with the virtual tunnel in a static state (0 Hz). The only variable differentiating this condition from the dynamic tunnel one is the motion of the stimulus as the structure and texture of the stimulus are identical in both conditions. In the *eyes closed* condition, participants performed two 68-s trials where they positioned their heads as if they were fixating the horizon but had their eyes closed. This condition was added to measure the extent to which visual input affected postural reactivity. In summary, all participants performed thirteen 68-s trials in the following chronological order: 2 static tunnel trials, 9 dynamic tunnel trials, and 2 eyes closed trials.

A trial was considered non-completed if a participant (1) lost balance during the trial (i.e., he or she could not remain standing) or (2) asked for the trial to be stopped. If a participant was unable to complete 2 of the 3 dynamic trials for a given oscillation frequency, his/her data were excluded from the statistical analyses. Differences in the percentage of completers ((number of completers in an age group divided by the total number of participants in this group) × 100) between age groups was nevertheless used as a qualitative index of development and is reported in the Results section.

Behavioral measures

The changes in posture were monitored using two measures, namely, BS (Faubert & Allard, 2004; Minshew et al., 2004; Schmuckler, 1997; Sparto et al., 2006) and vRMS (Faubert & Allard, 2004). Motion data points were sampled at a rate of 64 Hz. Our previous experiments with this setup (Faubert & Allard, 2004) and some pilot data with the stimuli presented here showed that the measures taken at the level of the head (sensor positioned on the stereo goggles) gave similar results as those taken when a sensor was positioned at the lower back (lumbar 2–3). This demonstrates that, at least under our present conditions, the postural response of our observers resembled that of an inversed pendulum motion pattern. We therefore selected to use only the sensor at the head, avoiding having to place two sensors, as opposed to the single head sensor, which is always required in our setup for the real-time geometrical correction of the observer's viewpoint.

BS is defined as the anterior–posterior displacement of a participant as a function of translation frequency (Faubert & Allard, 2004). More specifically, the postural response as a function of stimulus frequency was analyzed by using a Fast Fourier Transform (FFT) in Matlab generating a Power Spectrum Density (PSD). In order to extract Body Sway at the stimulation frequency from the PSD, the data were band-pass filtered (fourth-order Butterworth, zero phase shift, and band-passed for the given visual stimulus frequency). The same analysis was performed for each of the dynamic trials (each trial lasted 68 s; Figure 3).

Due to the developmental character of this study, heights could vary as a function of age group. We therefore used angular displacement as the dependent measure of postural reactivity as opposed to linear displacement. In order for the BS measures to take the

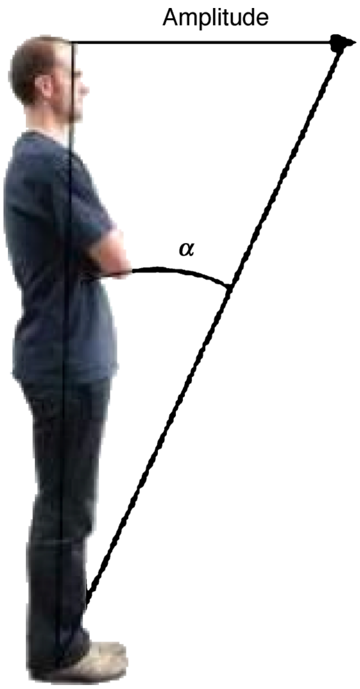

Figure 3. Angular displacement of a person.

participant's height into account, linear displacement measures (BS in cm) were converted to degrees of rotation (angular displacement), which corresponds to the inversed tangent (arctan) of linear displacement divided by the height of participant in cm. BS units are therefore discussed in terms of "minutes of rotation."

vRMS was used in order to quantify possible postural perturbations induced by the visual stimuli. It is defined as the root mean squared (RMS) of total body velocity in the horizontal (i.e., anterior–posterior "z axis" and medial-lateral displacements "x axis") and vertical (superior–inferior displacement "y axis") planes in centimeters per second (Faubert & Allard, 2004). In addition to taking into account vertical displacements, vRMS is distinct from the BS measure in that it is not computed relative to a single, specified frequency; it reflects body velocity at all frequencies. It is important to note that since more than 99% of the power was concentrated below 5 Hz, a low band-pass filter was performed on the data; this allowed removing the noise of the trackers for high temporal frequencies (Doyle, Hsiao-Wecksler, Ragan, Rosengren, 2007; Mahboobin, Loughlin, Redfern, & Sparto, 2005; Musolino, Loughlin, Sparto, Redfern, 2006). In the present study, we calculated the vRMS the same way as Faubert and Allard (2004) with the exception that we excluded information from the frequency of the visual stimulus condition so that the vRMS would better reflect postural perturbations that do not correspond with the visually driven BS response. For example, for the 0.25-Hz condition, we calculated the total vRMS without the data corresponding to the 0.25-Hz frequency. Excluding body movement corresponding to the fundamental frequency better represents an instability measure intended in the vRMS value, as the synchronized movement of the body with the stimulus does not represent instability per se.

Results

Qualitative data

The data from the 5- to 7-year-old age group were not included in statistical analyses because most of the children in that group were unable to complete the dynamic trials due to important losses of balance. Often, these participants had to remove their goggles in order not to fall during testing. Only 33% the 5- to 7-year-olds tested completed all the dynamic trials, a much lower rate than for the other age groups; 8- to 11-year-old group (71%), 12- to 15-year-old group (83%), 16 years + (100%). Although qualitative, these results suggest an over-reliance on visual input relative to proprioceptive and vestibular inputs to regulate posture at the youngest ages (5–7 years). Furthermore, as reflected by the increasing proportion of participants completing the dynamic trials with age, this over-reliance decreased as children became older.

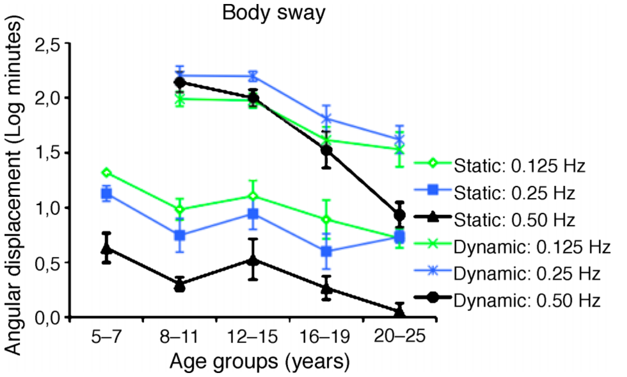

Figure 4. BS means (log minutes) as a function of age group and translation frequency. *SEM* are shown for each age group.

BS

Figure 4 clearly demonstrates that the natural BS when viewing the static baseline measure was quite different from the BS when presented with dynamic conditions. The three baseline functions here represent the sway amplitude for each of the three oscillation frequencies that were used as visual stimuli. Here we show only the static control (not eyes closed) because the data were virtually identical in both control conditions. Given the obvious difference between the static control and the dynamic conditions, we performed a 4 (age groups) × 3 (oscillation frequency) mixed factorial analysis of variance to probe the differences of interest for dynamic conditions only. As represented by Figure 4, there were significant main effects of age (BS decreased significantly with age), $F(3, 19) = 11.8987$, $p = 0.0001$, and Oscillation Frequency, $F(2{,}38) = 20.1596$, $p = 0.0001$. The Age Group × Oscillation Frequency interaction was significant, $F(6{,}38) = 7.2484$, $p = 0.0001$, suggesting that oscillation frequency did differentially affect BS as a function of age. Pairwise t-tests with Bonferroni corrections show that there is a significant difference between the 0.5 Oscillation Frequency condition and the other two conditions for the 20- to 25-year-old group while the 16- to 19-year-old group showed a significant difference only between 0.5 and 0.25 oscillation frequency conditions. The other age groups did not show significant differences between frequency conditions. To probe the age effect, pairwise comparisons were performed (Tukey) and revealed that the adult group's (20–25 years) BS mean was significantly lower than that of the 8- to 11- and 12- to 15-year-old groups but did not differ significantly from the 16- to 19-year-old group. The 16- to 19-year-old group also had significantly lower BS values than the 8- to 11- and 12- to 15-year-old groups.

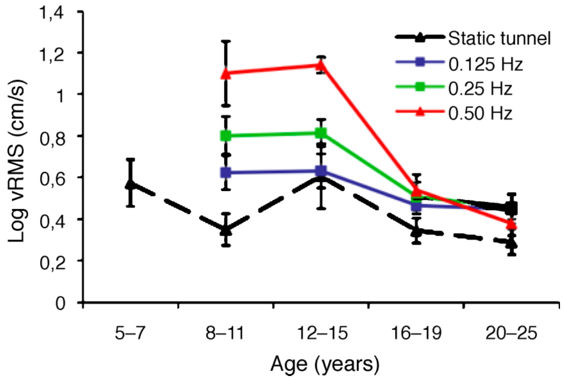

Figure 5. vRMS in log (cm/s) as a function of age and oscillation frequency. *SEM* are shown for each age group.

vRMS

As can be seen from Figure 5, the response pattern of the vRMS is quite different from the BS measures. Here there is less of a distinction between the control measure and the dynamic visual conditions. Again, here we show only the control condition with eyes open as there were no differences between eye open of closed control conditions. Because there is less distinction between the static and dynamic conditions, we have conducted a 4 (age groups) × 4 (oscillation frequency) mixed factorial analysis of variance with the static condition as a one of the oscillation frequency conditions. vRMS decreased significantly with age when collapsed across oscillation frequency, $F(3, 19) = 9.3133$, $p = 0.0005$. As shown in Figure 5, vRMS was significantly greater for the 8- to 11- and 12- to 15-year-old groups ($p < 0.05$) when compared to the adult group but was at adult levels for the 16- to 19-year-old group ($p > 0.05$). Furthermore, oscillation frequency had a different effect on instability for each age group, revealed by a significant Age Group × Oscillation Frequency interaction, $F(9, 57) = 4.9285$, $p = 0.0001$, where oscillation frequency affected instability for the 2 younger groups only (8- to 11- and 12- to 15-year-olds). For these age groups, instability was greatest for the 0.5-Hz frequency condition, followed respectively by 0.25-Hz and 0.125-Hz conditions. In general, from 16 years onward, instability was not affected by either age or frequency oscillation. As is obvious from Figure 5, the Oscillation Frequency condition was highly significant, $F(3, 57) = 20.0730$, $p = 0.0001$.

Discussion

The goal of this study was to assess the development of postural regulation in typically developing children reflected by their postural reactivity to dynamic, virtual visual environments. The first important finding is that for the youngest group (5- to 7-year-olds) visual input was disproportionately influential compared to proprioceptive and vestibular inputs on postural regulation. This was reflected by the qualitative finding that most participants in this age group were not able to complete the dynamic trials. Regarding the other age groups, body sway to different frequencies decreased significantly with age up until 16–19 years. Similarly, vRMS decreased significantly with age before reaching adult levels at around 16–19 years of age. These results are interpreted as suggesting an important transitory period regarding the maturation of the systems underlying sensorimotor integration at around 16 years of age.

As was mentioned earlier, oscillation frequency had a significant effect on BS, given that across age groups, the largest amount of sway was found for the 0.25-Hz condition. This is consistent with Sparto et al.'s (2006) findings where a peak in postural sway was observed at 0.25 Hz for 7- to 12-year-old children, suggesting that the use of dynamic cues for postural control is frequency dependent. Other studies have shown that the coupling of sway to optic flow was more important in the 0.2- to 0.3-Hz range; in other terms, 0.25 Hz could be a more natural speed of environmental movement, which makes it a frequency of choice for inducing sway (Dijkstra, Schöner, Giese, & Gielen, 1994; Giese, Dijkstra, Schnoer, & Gielen, 1996; Schöner, 1991).

The BS of the adult group at 0.5 Hz was clearly lower compared to the BS for the two other frequencies. This is in agreement with evidence from Stoffregen (1986) who found that when exposing adults to an oscillating room, a weaker correlation was observed between room movement and postural sway at higher frequencies compared to lower frequencies (frequency range: 0.2–0.8 Hz). Similarly, van Asten, Gielen, and van der Gon (1988) found that when adults were exposed to a rotating display above a 0.3-Hz frequency, compensatory lateral sway did not occur. In addition, when exposed to frequencies higher than 0.3 Hz, postural sway equaled that observed when participants had their eyes closed. In contrast to adults, infants and young children seem to use both high and low frequencies for postural control. Delorme, Frigon, and Lagacé (1989) found that 7- to 48-month-old infants that were exposed to an oscillating swinging room responded to a frequency as high as 0.52 Hz, as illustrated by the synchronicity of their postural sway with the room's oscillation frequency. Similarly, Bai (1991) found that infants aged between 5 and 13 months exposed to an oscillating room responded to frequencies in the 0.3-Hz to 0.6-Hz range. Finally, Schmuckler (1997) found that children between the ages of 3–6 years reacted to a range of 0.2–0.8 Hz swinging room oscillation frequencies but adults did not.

Similar to the BS findings, results from the present study clearly demonstrate a significant decrease in vRMS (or increase in stability) with age. For the 8- to 15-year-old group, there was an effect of frequency where the greatest instability was induced by the 0.5-Hz frequency, followed respectively by 0.25 Hz and 0.125 Hz. However, a frequency effect was not observed for the 16- to 19-year age groups. In addition, when averaged across frequency, mean vRMS for the 16- to 19-year-old group was adult-like, that is, it did not significantly differ from that of the 20- to 25-year-old group.

This finding is in accordance with previous data from Steindl, Kunz, Schrott-Fischer, and Scholtz (2006) who showed that the visual afferent system reached an adult level at 15 to 16 years of age with regards to the maintenance of postural balance (see also Aust, 1991; Hirabayashi & Iwasaki, 1995). Largo, Fischer, and Rousson (2003) found that static balance, as assessed by the Zurich Neuromotor Assessment continued developing until 18 years of age. Other studies have found that optimal stance stability is reached by the age of 15 years old (Cherng, Chen, & Su, 2001; Hirabayashi & Iwasaki, 1995; Peterka & Black, 1990).

A possible explanation for the decrease in BS at 0.5 Hz for the older versus the younger groups in our data could be inertia of the body that may differ for the older groups resulting in greater difficulty swaying at these higher frequencies. This may help explain why 0.5-Hz sway was greater than 0.125-Hz sway in the younger children but not the older. Although this is an interesting possibility, we do not believe that inertia is driving this difference. The reason is that we have recently conducted some measures across life span (Greffou & Faubert, 2008) and found that older adults, who presumably have similar inertia as the young adults, have responses identical to the younger observers in the present study for the 0.5-Hz condition. That is, the 0.5-Hz BS was greater in the older observers than the young adults and therefore cannot be the result of differences in body inertia.

In the following sections, the present findings will be discussed within the context of existing frameworks implicating different regulatory systems involved in visuo-motor integration as a function of age. Five different frameworks will be addressed:

1. visuo-motor brain processing that underlies postural regulation reaches adult levels at around 16 years of age;
2. children rely more heavily on visual information to regulate their posture due to their immature vestibular and somatosensory systems;
3. children have greater difficulty dealing with conflicting sensory information, hence exhibiting postural instability;
4. the habituation phenomenon, which is a gain in experience in the control of posture; and finally
5. Woollacott and Shumway-Cook's (1990) systems theory of development where children progressively acquire systems that allow them to control posture.

Visuo-motor processing that underlies postural regulation requires the activation of many brain areas. A study by Slobounov et al. (2006) has looked at the neural underpinning of postural responses to visual field motion using virtual reality stimuli. They found significant activation of motion sensitive areas V5/MT (Middle Temporal area) and STS (Superior Temporal Sulcus), suggesting that the brain has an extensive but unified visual motion processing system (this finding was true for an anterior–posterior virtual room displacement stimulus at 0.3 Hz). They also observed the activation of prefrontal and parietal areas bilaterally which they believed was due to fronto-parietal network for attentional modulations; this finding is consistent with those of Friston, Holmes, Poline, Price, and Frith (1996) who suggested a supra-modal role of the prefrontal cortex in attention operating both in the mnemonic and sensorimotor domains. Slobounov et al. (2006) suggest that there is a functional interaction between modality specific posterior-visual and frontal–parietal areas that subserve visual attention and other perceptual-motor tasks. Moreover, the bilateral activation of the parietal cortex can be explained by the fact that parietal systems play an important role in the perception and the analysis of complex motion patterns and in the control of planned action. They observed a bilateral activation of the cerebellum during the presentation of a moving virtual room; the cerebellum is involved in the execution of motor tasks but also in the cognitive task of judgment of motor activity and in the timing system providing precise temporal representation across motor tasks. Finally the ACC (Anterior Cingulate Cortex) was activated, which is thought to be responsible for attentional control. As demonstrated above, there are many brain areas solicited for postural control. It is quite probable, therefore, that the integration of these brain systems would take some time to mature and our data suggest that this would occur at the earliest around 16 to 19 years of age.

Some have argued that children rely more heavily on visual cues than adults to control their posture due to their inability to use the vestibular and somatosensory information available (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985). It nonetheless appears, in the light of our findings, that the effects of age and of oscillation frequency on instability are contingent on *dynamic* visual input information and not on immature vestibular motor systems. If the vestibular and somatosensory systems were immature in children, we would have observed a difference in instability even in the presence of a static environment (static tunnel), which was not supported by our data. Peterka and Black (1990) also demonstrated that instability for children was no different from that of adults when exposed to a static environment.

An existing theory proposes that children rely more heavily on visual input to regulate their posture compared to adults because they have difficulty dealing with conflicting sensory information (Barela, Jeka, & Clark, 2003; Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985). Forssberg and Nashner (1982) have suggested that children below the age of 7.5 years are unable to reweigh multiple sensory inputs, which is congruent with the qualitative results demonstrating that children below 8 years of age were unable to complete the dynamic trials. In contrast, the Bair, Kiemel, Jeka, and Clark (2007) study assessing somatosensory vs. visual inputs reweighing in children aged 4 to 10 years has shown that children can reweigh multisensory inputs from 4 years on. However, the amount of reweighing increased with age and reweighing contributed to a more stable and flexible control of upright stance. Along these lines, a possible explanation for the observed stability plateau in the present study could be that around 16 years of age, children become very competent at dealing with conflicting sensory information or at reweighing the different sensory afferences (e.g., when proprioceptive and vestibular inputs remain unchanged while the visual input is altered).

The fact that we did not observe an effect of frequency on vRMS in participants whose ages were 16 years onward could potentially be explained by the "Habituation" phenomenon. This phenomenon was addressed by Schmuckler (1997) who found that in later trials, body sway to dynamic visual stimuli was significantly decreased when compared to identical earlier trials for the same participant. Hence, it may be possible to generalize this phenomenon to everyday experiences, in that, older teenagers and adults may have habituated to dynamic environments to which they have been exposed for a longer period than the younger children therefore reacting less.

Among the different developmental theories on postural control lies Woollacott and Shumway-Cook's (1990) who have argued in favor of two different explanations:

1. The "strict vertical hierarchy hypothesis," which claims that infants first use a cephalocaudal gradient and a primitive reflex system in establishing stability but develop more mature higher nervous system centers (in the cortex) that take over the function of postural control; and
2. the "Systems Theory," where the development of independent stance emerges from the interaction among multiple neural and biomechanical components.

These components are the following: postural muscle response synergies; visual, vestibular, and somatosensory systems for detecting loss of balance; adaptive systems for modifying sensory and motor systems to changes in task; muscle strength; joint range of motion; and body morphology. According to this hypothesis, transitory phases of development would occur whenever one or many of the components mature. A possible explanation for our study's findings would be that all of these components may finish maturing around 16 to 19 years of age and that important ones become developed after 8 years of age as reflected by a higher stability and a lower postural reactivity of children between 8 and 15 years old compared to the children of 5 to 7 years old. Similar findings were reported by Shumway-Cooke and Woollacott (1985) who observed that the onset and timing of the response of 4- to 6-year-old children to platform perturbations were markedly different from that of older children. During development of postural control, there are musculoskeletal and body morphology changes such as height, center of mass, and foot length. Depending on the combination of these different components, a person will choose either of these three strategies:

1. the ankle strategy in which balance adjustments are made at the ankle joint,
2. the hip strategy where adjustments are made at the hip, and
3. the suspensory strategy in which the person flexes at the knee, ankle, and hip to lower the center of gravity toward the base of support.

As children's heights change with the passage of time, resulting musculoskeletal changes influence their stability but also the type of strategy that will be chosen to achieve stability. In the light of our study, perhaps musculoskeletal development achieves adult levels around 16–19 years of age.

Finally, different muscle synergies are exhibited during balance control depending on age. For example, Sundermier, Woollacott, Roncesvalles, and Jensen (2001) found that children between the ages of 4–10 years used different muscle synergies than the younger children who were 1 and 2 years old. Changes in muscle synergies probably continue to develop above the age of 10 years and could possibly account for the differences observed in our study.

Conclusion

Other factors aside from age could have affected our results such as weight, height, physical activity history, fatigue levels during testing, etc. For instance, Schmuckler (1997) found that body measures like height, leg length, and weight were positively correlated with postural sway. This being said, we believe that the sensitivity and ecological validity of the immersive virtual reality technology used in this study combined with the wide range of ages that we have investigated has helped us gather strong evidence for at least one important transition phase of sensorimotor development, existing between 16 and 19 years of age. This paradigm could be useful for the assessment and diagnosis of clinical populations, most particularly, neurodevelopmental disorders (i.e., autism, spectrum disorders), age-related neurodegenerative disorders (such as Alzheimer and Parkinson's disease), and other neurological patient populations such as persons suffering from head traumas, strokes, etc.

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References

Assaiante, C., & Amblard, B. (1993). Ontogenesis of head stabilization in space during locomotion in children: Influence of visual cue. *Experimental Brain Research, 93,* 499–515. [PubMed]

Aust, G. (1991). Vestibular disorders in old age. *HNO, 39,* 460–466. [PubMed]

Bai, D. L. (1991). *Visual control of posture during infancy*. Unpublished doctoral dissertation. University of Virginia.

Bair, W. N., Kiemel, T., Jeka, J. J., & Clark, J. E. (2007). Development of multisensory reweighting for posture control in children. *Experimental Brain Research, 183,* 435–446. [PubMed]

Barela, J. A., Jeka, J. J., & Clark, J. E. (2003). Postural control in children. Coupling to dynamic somatosensory information. *Experimental Brain Research, 150,* 434–442. [PubMed]

Cherng, R. J., Chen, J. J., & Su, F. C. (2001). Vestibular system in performance of standing balance of children and young adults under altered sensory conditions. *Perceptual and Motor Skills, 92,* 1167–1179. [PubMed]

Delorme, A., Frigon, J. Y., & Lagacé, C. (1989). Infants' reactions to visual movement of the environment. *Perception, 18,* 667–673. [PubMed]

Dijkstra, T. M., Schöner, G., Giese, M. A., & Gielen, C. C. (1994). Frequency dependence of the action-perception cycle for postural control in a moving visual environment: Relative phase dynamics. *Biological Cybernetics, 71,* 489–501. [PubMed]

Doyle, R. J., Hsiao-Wecksler, E. T., Ragan, B. G., Rosengren, K. S. (2007). Generalizability of center of pressure measures of quiet standing. *Gait & Posture, 25,* 166–171. [PubMed]

Faubert, J., & Allard, R. (2004). Effect of visual distortion on postural balance in a full immersion stereoscopic environment. In A. J. Woods, J. O. Merrit, S. A. Benton, & M. T. Bolas (Eds.), *Stereoscopic displays and virtual reality systems XI* (vol. 5291, pp. 491–500). Proceedings of SPIE-IS&T Electronic Imaging, SPIE.

Forssberg, H., & Nashner, L. M. (1982). Ontogenic development of postural control in man: Adaptation to altered support and visual conditions during stance. *Journal of Neuroscience, 2,* 545–552. [PubMed] [Article]

Foster, E. C., Sveistrup, H., & Woollacott, M. H. (1996). Transitions in visual proprioception: A cross-sectional developmental study of the effect of visual flow on postural control. *Journal of Motor Behavior, 28,* 101–112. [PubMed]

Friston, K. J., Holmes, A., Poline, J. B., Price, C. J., & Frith, C. D. (1996). Detecting activations in PET and fMRI: Levels of inference and power. *Neuroimage, 4,* 223–235. [PubMed]

Giese, M. A., Dijkstra, T. M., Schöner, G., & Gielen, C. C. (1996). Identification of the nonlinear state-space dynamics of the action-perception cycle for visually induced postural sway. *Biological Cybernetics, 74,* 427–437. [PubMed]

Grasso, R., Assaiante, C., Prévost, P., & Berthoz, A. (1998). Development of anticipatory orienting strategies during locomotor tasks in children. *Neuroscience and Biobehavioral Reviews, 22,* 533–539. [PubMed]

Greffou, S., & Faubert, J. (2008). Life-span study of visually driven postural reactivity: A fully immersive virtual reality approach [Abstract]. *Journal of Vision, 8*(6):426, 426a, http://journalofvision.org/8/6/426/, doi:10.1167/8.6.426.

Hay, L., Fleury, M., Bard, C., & Teasdale, N. (1994). Resolving power of the perceptual- and sensorimotor systems in 6- to 10-year-old children. *Journal of Motor Behavior, 26,* 36–42. [PubMed]

Hirabayashi, S., & Iwasaki, Y. (1995). Developmental perspective of sensory organization on postural control. *Brain & Development, 17,* 111–113. [PubMed]

Keshner, E. A., & Kenyon, R. V. (2004). Using immersive technology for postural research and rehabilitation. *Assistive Technology, 16,* 54–62. [PubMed]

Largo, R. H., Fischer, J. E., & Rousson, V. (2003). Neuromotor development from kindergarten age to adolescence: Developmental course and variability. *Swiss Medical Weekly, 133,* 193–199. [PubMed] [Article]

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing human infants. *Perception & Psychophysics, 15,* 529–532.

Lee, H. Y., Cheng, R. J., & Lin, C. H. (2004). Development of a virtual reality environment for somatosensory and perceptual stimulation in the balance assessment of children. *Computers in Biology and Medicine, 34,* 719–733. [PubMed]

Mahboobin, A., Loughlin, P. J., Redfern, M. S., & Sparto, P. J. (2005). Sensory re-weighting in human postural control during moving-scene perturbations. *Experimental Brain Research, 167,* 260–267. [PubMed]

Minshew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology, 63,* 2056–2061. [PubMed]

Musolino, M. C., Loughlin, P. J., Sparto, P. J., Redfern, M. S. (2006). Spectrally similar periodic and non-periodic optic flows evoke different postural sway responses. *Gait & Posture, 23,* 180–188. [PubMed]

Nolan, L., Grigorenko, A., & Thorstensson, A. (2005). Balance control: Sex and age differences in 9- to 16-year-olds. *Developmental Medicine and Child Neurology, 47,* 449–454. [PubMed]

Peterka, R. J., & Benolken, M. S., (1995). Role of somatosensory and vestibular cues in attenuating visually induced human postural sway. *Experimental Brain Research, 105,* 101–110. [PubMed]

Peterka, R. J., & Black, F. O. (1990). Age-related changes in human posture control: Sensory organization tests. *Journal of Vestibular Research, 1,* 73–85. [PubMed]

Riach, C. L., & Hayes, K. C. (1987). Maturation of postural sway in young children. *Developmental Medicine and Child Neurology, 29,* 650–658. [PubMed]

Schmuckler, M. A. (1997). Children's postural sway in response to low- and high-frequency visual information for oscillation. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 528–545. [PubMed]

Schöner, G. (1991). Dynamic theory of action-perception patterns: The "moving room" paradigm. *Biological Cybernetics, 64,* 455–462. [PubMed]

Shumway-Cook, A., & Woollacott, M. H. (1985). The growth of stability: Postural control from a development perspective. *Journal of Motor Behavior, 17,* 131–147. [PubMed]

Slobounov, S., Wu, T., Hallett, M., Shibasaki, H., Slobounov, H., & Newell, K. (2006). Neural underpinning of postural responses to visual field motion. *Biological Psychology, 72,* 188–197. [PubMed]

Sparto, P. J., Redfern, M. S., Jasko, J. G., Casselbrant, M. L., Mandel, E. M., & Furman, J. M. (2006). The influence of dynamic visual cues for postural control in children aged 7–12 years. *Experimental Brain Research, 168,* 505–516. [PubMed]

Steindl, R., Kunz, K., Schrott-Fischer, A., & Scholtz, A. W. (2006). Effect of age and sex on maturation of sensory systems and balance control. *Developmental Medicine and Child Neurology, 48,* 477–82. [PubMed]

Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Perception & Psychophysics, 39,* 355–360. [PubMed]

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optical flow in stance and locomotion in young walkers. *Perception, 16,* 113–119. [PubMed]

Sundermier, L., Woollacott, M., Roncesvalles, N., & Jensen, J. (2001). The development of balance control in children: Comparisons of EMG and kinetic variables and chronological and developmental groupings. *Experimental Brain Research, 136,* 340–350. [PubMed]

van Asten, W. N., Gielen, C. C., & van der Gon, J. J. (1988). Postural movements induced by rotations of visual scenes. *Journal of the Optical Society of America A, Optics and Image Science, 5,* 1781–1789. [PubMed]

Woollacott, M. H., & Shumway-Cook, A. (1990). Changes in posture control across the life span–A systems approach. *Physical Therapy, 70,* 799–807. [PubMed]