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A virtual reality approach to the study of visually driven postural control in developing and aging humans

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Résumé

L'être humain utilise trois systèmes sensoriels distincts pour réguler le maintien de la station debout: la somesthésie, le système vestibulaire, et le système visuel. Le rôle de la vision dans la régulation posturale demeure peu connu, notamment sa variabilité en fonction de l'âge, du type développemental, et des atteintes neurologiques. Dans notre travail, la régulation posturale induite visuellement a été évaluée chez des participants au développement et vieillissement normaux âgés de 5-85 ans, chez des individus autistes (développement atypique) âgés de 12-33 ans, ainsi que chez des enfants entre 9-18 ans ayant subi un TCC léger. À cet effet, la réactivité posturale des participants en réponse à un tunnel virtuel entièrement immersif, se mouvant à trois niveaux de vélocité, a été mesurée; des conditions contrôles, où le tunnel était statique ou absent, ont été incluses.

Les résultats montrent que la réactivité (i.e. instabilité) posturale induite visuellement est plus élevée chez les jeunes enfants; ensuite, elle s'atténue pour rejoindre des valeurs adultes vers 16-19 ans et augmente de façon linéaire en fonction de l'âge après 45 ans jusqu'à redevenir élevée vers 60 ans. De plus, à la plus haute vélocité du tunnel, les plus jeunes participants autistes ont manifesté significativement moins de réactivité posturale comparativement à leurs contrôles; cette différence n'était pas présente chez des participants plus âgés (16-33 ans). Enfin, les enfants ayant subi un TCC léger, et qui étaient initialement modérément symptomatiques, ont montré un niveau plus élevé d'instabilité posturale induite visuellement que les contrôles, et ce jusqu'à 12 semaines post-trauma malgré le fait que la majorité d'entre eux (89%) n'étaient plus symptomatiques à ce stade. En somme, cela suggère la présence d'une importante période de transition dans la maturation des systèmes sous-tendant l'intégration sensorimotrice impliquée dans le contrôle postural vers l'âge de 16 ans, et d'autres changements sensorimoteurs vers l'âge de 60 ans; cette sur-dépendance visuelle pour la régulation posturale chez les enfants et les aînés pourrait guider l'aménagement d'espaces et l'élaboration d'activités ajustés à l'âge des individus. De plus, le fait que l'hypo-réactivité posturale aux informations visuelles chez les autistes dépende des caractéristiques de l'environnement visuel et de l'âge chronologique, affine notre compréhension des anomalies sensorielles propres à l'autisme. Par ailleurs, le fait que les enfants ayant subi un TCC léger

montrent des anomalies posturales jusqu'à 3 mois post-trauma, malgré une diminution significative des symptômes rapportés, pourrait être relié à une altération du traitement de l'information visuelle dynamique et pourrait avoir des implications quant à la gestion clinique des patients aux prises avec un TCC léger, puisque la résolution des symptômes est actuellement le principal critère utilisé pour la prise de décision quant au retour aux activités. Enfin, les résultats obtenus chez une population à développement atypique (autisme) et une population avec atteinte neurologique dite transitoire (TCC léger), contribuent non seulement à une meilleure compréhension des mécanismes d'intégration sensorimotrice sous-tendant le contrôle postural mais pourraient aussi servir comme marqueurs sensibles et spécifiques de dysfonction chez ces populations.

Mots-clés : posture, équilibre, vision, développement/vieillissement sensorimoteur, autisme, TCC léger symptomatique, réalité virtuelle.

Abstract

Maintaining upright stance is essential for the accomplishment of several goal-directed behaviors, such as walking. Humans use three distinct sensory systems to regulate their posture: the somatosensory, the vestibular and the visual systems. The role of vision in postural regulation remains poorly understood, notably its variability across the life-span, developmental type and neurological insult. Hence, visually-driven postural regulation was examined in typically developing and aging participants (5-85 years-old), as well as in atypically developing individuals with autism (12-33 years-old) and in children having sustained mTBI (9-18 years-old). In order to do so, participants' postural reactivity was assessed in response to a fully immersive virtual tunnel moving at 3 different velocities; control conditions were also included wherein the tunnel was either static or absent.

Results show that visually-induced postural reactivity was strongest in young children, then attenuated to become adult-like between 16-19 years of age, and started increasing again linearly with age after 45 years until becoming strong again around 60 years. Moreover, at the highest tunnel velocity, younger autistic participants showed significantly less postural reactivity compared to age-matched controls and young adults (16-33 years-old). Finally, children having sustained mTBI, who were initially moderately symptomatic, exhibited increased visually-induced instability compared to their matched controls up to 12 weeks post-injury, although most of them (89%) were no longer highly symptomatic. Altogether, this suggests the presence of an important transition period for the maturation of the systems underlying sensorimotor integration in postural control at around 16 years of age, and further sensorimotor changes after 60 years of age; this over-reliance on vision for postural regulation in childhood and late adulthood could guide the design of age-appropriate facilities/ activities. Furthermore, the fact that postural hypo-reactivity to visual information present in autism is contingent on both the visual environment and on chronological age, enhances our understanding of autism-specific sensory anomalies. Additionally, the fact that children with mTBI show balance anomalies up to 3 months post-injury, even when they are no longer highly symptomatic may be related to altered processing of dynamic visual information and

could have implications for the clinical management of mTBI patients, since symptoms resolution is commonly used as a criterion for return to activities. Finally, results stemming from populations with atypical development (autism) and with so-called transient neurological insult (mild TBI) not only contribute to enhance our understanding of sensorimotor integration mechanisms underlying postural control, but could also consist of sensitive and specific markers of dysfunction in these populations.

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List of abbreviations

3D……………...	three dimensions
A…...……………	amplitude
ACC…………...	anterior cingulate cortex
ADHD…………	attention deficit hyperactivity disorder
ADI……………	autism diagnosis interview
ADOS…………	Autism Diagnosis Observation Schedule
ANOVA…..…...	analysis of variance
ANCOVA…......	analysis of covariance
arctan…………..	inversed tangent
ASD……………	autism spectrum disorders
BESS…………..	Balance Error Scoring System
BOS…………...	base of support
BOT2………….	Bruininks-Oseretsky Test of Motor Proficiency, 2nd Edition
BS……………...	body sway
CAVE…………	Cave Automatic Virtual Environment
cd/m^2…………...	candela per square meter
cm……………...	centimeter
cm/s……………	centimeters per second
CNS...................	central nervous system
COM…………..	center of mass
deg/s…………....	degrees per second
DSM-IV……….	Diagnostic and Statistical Manual of Mental Disorders, 4th Edition
DSM-V………...	Diagnostic and Statistical Manual of Mental Disorders, 5th Edition
EC……………...	eyes closed condition
EEG……………	electroencephalography
f………………...	frequency
FFT……………	fast fourier transform
GABA................	gamma-aminobutyric acid
HFA……………	high functioning autism
Hz………………	hertz
IQ………………	intellectual quotient
LFA……………	low functioning autism
log……………...	logarithm
LS-mTBI………	low-symptomatic mild traumatic brain injury
mTBI…………..	mild traumatic brain injury
m^2………………...	squared meter
MS-mTBI……...	moderately symptomatic mild traumatic brain injury

PCS-R…………	Post-Concussion Symptom Scale-Revised
PP……………...	postural perturbations
PSD……………	power spectrum density
s………………..	second
SD……………..	standard deviation
SEM…………...	standard error of the mean
ST……………..	static tunnel condition
STS……………	superior temporal sulcus
t………………..	time in seconds
T………………	period
TD……………..	typically developing
V5……………..	extrastriate cortical area 5
VR……………..	virtual reality
vRMS………….	velocity root mean squared

To my parents, Madjid and Farida.

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Introduction

Overview of the Human Postural Control System

Humans have undergone thousands of years of behavioral and postural evolutions, among them the acquisition of bipedalism, an essential feature to the accomplishment of daily-life activities, such as locomotion and reaching for objects (Harcourt-Smith & Aiello, 2004). Upright human posture is inherently unstable and can be defined as the ability to maintain the body's center of mass (COM) within the base of support (BOS, defined by feet position on the ground) during standing, while resisting the destabilizing effects of gravity and external disturbances.

In order to resist internal and external perturbations to achieve balance of the COM with respect to the BOS, the postural control system enlists the sensory system, the musculoskeletal system, and the central nervous system. The complex interactions between these systems allow for the integration of sensory input (information about the coordinates of the body's position) and for the production of adequate motor output by the central nervous system to adjust posture (Hur, 2012). Additionally, regulatory subsystems involved in posture have been identified in healthy humans: a passive system based on postural reflexes (stemming from tissues around joints), a feedforward anticipatory system based on cognition and environmental context (e.g., one will adjust his movements if he/she is about to step on a slippery surface), and a feedback control system based on sensory systems.

Active torque generated by the feedback control system is often considered to be the dominant contributor to quiet stance control (Peterka, 2002). In order for the nervous system to generate corrective torques for the maintenance of balance, three feedback sensory systems provide it with information regarding the spatial orientation of the body: 1) the <u>vestibular system</u>, which instructs on the position of the head with respect to gravity and information about motion through linear and angular acceleration of the head; 2) the <u>proprioceptive system</u>, which senses the position of body parts with respect to their neighboring body parts

through muscles, joints, and cutaneous receptors; 3) the <u>visual system</u> which provides information about the position of objects in space and relative position of the body with respect to the visual environment. Sensory afferent information is processed and integrated within appropriate centers in the brain; subsequently, motor centers produce appropriate motor programs and send efferent neural signals in order to innervate target muscles that will maintain the balance of the COM within the BOS (Latash, 2008 in Hur, 2012).
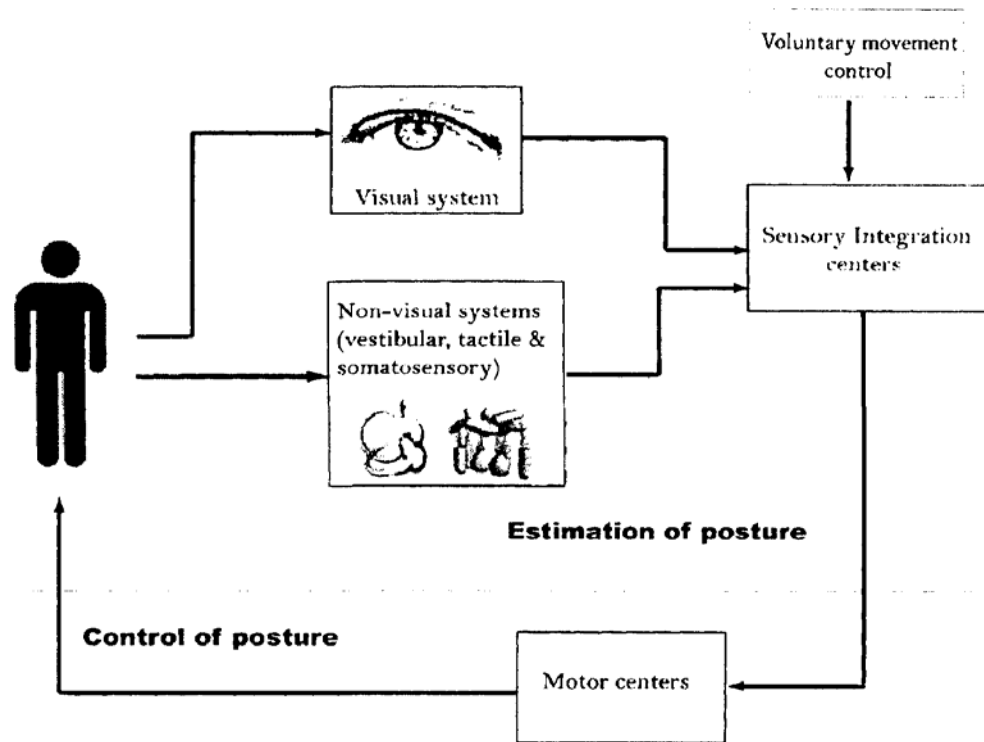
I-Figure 1. A summary of the processes involved in postural control (figure from Dokka, 2009).

Non-Visual Sensory Contributions to Postural Control

It is a well known fact that sensory information play a crucial role in postural control and the role of the vestibular, proprioceptive and visual contribution have been extensively studied (Roll et al. 1980, Dijkstra, Fitzpatrick and McCloskey 1994 in Hadders-Algra &

Carlberg, 2008), as well at the role of cutaneous information of the feet and fingers more recently (Jeka, 1997 in Hadders-Algra & Carlberg, 2008).

The Vestibular System is traditionally linked to postural stability. When the vestibular organ behind the ear of a person is stimulated, the body leans in particular directions depending on the position of the head and on the polarity of the current applied. Due to the slow rate of change of vestibular signals, a recent hypothesis has been formulated according to which the vestibular signals would serve as a reference frame for estimation of sensory signals from other modalities (Mergner et al. 2003 dans Hadders-Algra & Carlberg, 2008); an example of this can be seen when very slow movements of the head with respect to the trunk are capable of inducing strong postural illusions. Likewise, a recent study has shown that the vestibular system is not of paramount importance in the regulation of posture, as illustrated by the fact that bilateral labyrinthine-defective subjects did not do significantly worse than control participants on a task of judgement of earth-referenced horizon during sagittal body tilt whilst seated. This was suggestive that somatosensory input could convey as much graviceptive information as the vestibular system in the context of the task used (Bringoux, Mezey, Faldon, Gresty, & Bronstein, 2007).

The Proprioceptive System: The importance of proprioceptors for balance can be seen by the effect that vibration stimulation applied to tendons can have on posture. Indeed, proprioceptors are located in the leg muscles, joints and tendons and inform the brain about the configuration of the limbs and their positions relative to the trunk. Since sensory endings in muscle spindles are a major source of information for this purpose, stimulating them with low amplitude high frequency vibrations leads to motor consequences such as muscle contraction. If one keeps his/her eyes closed and vibration is applied to the tendon of a muscle implicated in postural control, an inclination of the body can be seen backwards (e.g., Achilles tendon, Eklund and Hagbarth 1967 in Hadders-Algra & Carlberg, 2008); this effect is so strong that it can make a person lose balance and step; this is likely caused by the fact that a vibration is interpreted by the brain as a stretched muscle, which is associated to changes in body orientation.

The Cutaneous System: It has been shown that during quiet standing, light touch by a finger tip on the index finger (Holden et al. 1994 in Hadders-Algra & Carlberg, 2008), neck, or the head (Krishnamoorthy et al. 2002 in Hadders-Algra & Carlberg, 2008) can greatly attenuate postural sway and even more so than providing vestibular information (Hadders-Algra & Carlberg, 2008).

Vision and Postural Control

Visual information assuredly has a strong influence on our balance control. This fact has been empirically demonstrated (Peterka, 2002; Slobounov et al., 2006) and one can easily think of a situation where moving visual scenes have influenced his/her balance. For example, when one is sitting in a stationary train carriage and notices another train moving alongside, he/she will likely feel as though it is the stationary train that has moved (Hadders-Algra & Carlberg, 2008). Indeed, when an individual views his/her visual surroundings move, he/she is likely to have the perception of moving in the opposite direction to that of the visual stimulus, thereby creating an impression of self-motion; the person consequently responds to these changes by producing appropriate body movements (Dokka, 2009). The nervous system employs visual cues by encoding them via retinal coordinates and specifies relative displacement between an individual and the external world (Pouget, Ducom, Torri, & Bavelier, 2002). The neural networks involved in such operations are complex and extensive.

Over the past century, the notion that posture was primarily the result of reflexes and muscle tone was changed and is now considered to be an active process involving all of the nervous system (Massion et al. 2004 in Hadders-Algra & Carlberg, 2008) and vertical posture is believed to be the result of the interaction between the cerebellum, basal ganglia and the cerebral cortex. Since the postural control system is complex and multifaceted, it can be adversely affected by a multitude of factors such as 1) age, 2) atypical development, 3) traumatic injuries, etc... (Hadders-Algra & Carlberg, 2008):

1) Indeed, the relative weight of vision in comparison with other sensory modalities involved in postural control has been shown to be subject to changes throughout the life-span, but the exact age at which changes occur is variable across studies. Several 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; Grasso et al., 1998), which suggests that these sensory systems operate differentially during childhood (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985). Peterka and Black (1990) measured postural control of participants whose ages ranged from 7 to 80 years and found age-related increases in sway for conditions involving transient dynamic visual information (i.e., optic flow). Moreover, 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. Other studies have demonstrated that younger children manifest a stronger dependence on visual input for postural control, where a shift away from visual control is evidenced by 7 to 8 years of age (Assaiante & Amblard, 1993; Hay, Fleury, Bard, & Teasdale, 1994). Also, Sparto et al., (2006) study used a VR system to create an immersive visual environment and found that children from 7 to 12 years of age showed more postural reactivity to the stimulation than the adult group (N.B. they did not assess other age groups in children). 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. Although 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), findings diverge with regards to the age at which visuo-motor maturation occurs in the context of postural control.

Additionally, these sensory systems also seem to operate differentially in early adulthood compared to more advanced ages. Some studies have reported a return of the over-reliance on vision in postural control at more advanced ages. For example, Hytonen, Pyykko,

Aalto, & Starck, (1993) have assessed the sway velocity of 6 to 90 year-old healthy participants with both eyes open and eyes closed and found that the amount of sway showed a U-shaped curve, where the visual system was of most importance for balance control in children and in older adults (note that the visual stimulus was not dynamic). Other studies have shown that older adults were generally more destabilized by optical flow stimuli than younger adults (Sundermier, Woollacott, Jensen, & Moore, 1996; Wade, Lindquist, Taylor, & Treat-Jacobson, 1995). Moreover, Era, et al., (2006)'s study has shown that a deterioration in balance function (as measured by increased sway on a force platform with eyes open) starts around middle-age and further accelerates at about 60 years upwards. In a study by Hytonen (1993), the greatest postural stability was present at around 50 years of age and the visual system was found to be of most importance for balance control in their eldest participants (when comparing performances on eyes open and eyes closed). Poulain & Giraudet, (2008) used a virtual reality environment to assess if 44 to 60 year-old individuals would significantly differ from younger adults as it pertains to postural control in response to two visual tasks (a recognition task and a Rapid Serial Visual Presentation task) as measured on a stabilometric platform; they found that 44 to 60 year-old participants showed greater visual sensitivity in posture control (i.e., greater instability) compared to young adults and that their postural stability depended on task constraints.

2) As was previously mentioned, the complexity of the postural control system makes it vulnerable and affected by a multitude of factors or events. For example adults with cerebellar pathology exhibit postural difficulties manifested by increased sway of the trunk and a wide base of support while walking and standing Babinski 1899, Van de Werrenburg et al. 2005, in Hadders-Algra & Carlberg, 2008). Furthermore, the observation of postural behavior of persons with Parkinson's disease, characterized by postural instability and problems modifying patterns and magnitude of postural adjustments to changes in postural demands (Horak et al., 2005 in Hadders-Algra & Carlberg, 2008), sheds light on the role of the basal ganglia in postural control. Furthermore, patients with supratentorial strokes have increased our knowledge about the role of the motor cortices and corticospinal pathways in postural control as these patients manifested postural instability linked to inaccurate timing

and magnitude of postural activity (Geurts et al., 2005 in Hadders-Algra & Carlberg, 2008). Aside from these types of injuries to the CNS, other alterations thereof seem to affect processing of visual information, and in turns the efficiency of feedback control of posture. These alterations can either be innate (e.g., developmental disorders) or acquired (e.g., traumatic events).

Indeed, autism is a good example of innate anomalies of the CNS of neurogenetic origin, wherein motor and postural anomalies have long been documented. Given autism's atypical *''perceptual signature''*, characterized by a decreased ability or optional processing for complex types of information requiring either integrative, dynamic or global analysis (see Mottron and Burack 2001; Mottron et al. 2006); Dakin and Frith 2005; Behrmann et al. 2006; Bertone and Faubert 2006; Happe and Frith 2006; Simmons et al. 2009; Bertone et al. 2010), altered postural regulation can be expected since visual information processing is involved in several visually-contingent behaviors, including maintaining posture, or balance. Although anomalies of motor behavior, most often described as associated symptoms, (i.e., either clumsiness, fine/gross motor deficits, apraxia, alterations in motor milestone development, etc.…) have been well documented in autism (Teitelbaum et al. 1998; Ghaziuddin and Butler 1998; Ming et al. 2007), relatively few studies have directly assessed either balance and/or postural reactivity in autism. In one such study, Gepner et al. (1995) reported an attenuation of reactivity to a radiating full-field optic flow stimulus, which typically induces the illusory perception of self motion, particularly for fast visual motion (Gepner and Mestre, 2002a). This study involved a small group of five young children with autism whose ages ranged between 4 and 7 years (and whose intellectual level of functioning was not documented). Gepner and colleagues concluded that persons with autism, especially those with low functioning autism (LFA), were insensitive to dynamic visual information with regards to posture compared to control participants, which probably originated from an impairment in motion perception. These and other results related to the perception of both social and non-social information (Gepner and Mestre 2002a) have been used to propose that a ''rapid visual motion integration deficit'' (Gepner and Mestre 2002b), and more recently, a ''temporo-spatial processing disorder'' (Gepner and Féron 2009) may underlie postural anomalies in autism. Subsequent

studies assessing posture in autism have manipulated proprioceptive input by having participants stand on foam (or not) under different visual conditions. For example, Molloy et al. (2003) demonstrated that on average, autistic children were less stable when standing passively and blindfolded, thus eliminating visual cues, whether or not proprioceptive information was modified. Reflecting over-reliance on visual input for maintaining balance in the autism/ASD group, this result was interpreted as evidence for a multi-modal dysfunction in the integration of information originating from visual, somatosensory, and vestibular afferences in autism. Using a larger sample of 79 high-functioning autistic participants aged between 5 and 52 years, Minshew et al. (2004) demonstrated that the postural stability of autistic participants was reduced when proprioceptive input was disrupted by a sway-referenced platform. In addition, results demonstrated that postural control started to develop later in the autism group (12 years of age compared to 5 years in the control group) and never reached neuro-typical, adult-like levels.

3) Traumatic Brain Injury (TBI) is an example of acquired alteration of the CNS. Amongst the many physical symptoms that can arise following a TBI, balance problems have been commonly reported in adults (Cavanaugh et al., 2006). Some studies have focused on the visual component involved in atypical postural behavior following mild TBI (mTBI): In a study performed on adults, it was suggested that sustaining mTBI induces an over-reliance on visual input when regulating posture in adults a few days post-injury (Rubin, Woolley, Dailey, & Goebel, 1995). Another study has shown that college athletes with mTBI failed to appropriately use visual cues to regulate their posture when assessed using the Sensory Organization Test (SOT) (Guskiewicz, Riemann, Perrin, & Nashner, 1997). Additionally, Slobounov et al., (2006) used a virtual reality environment to investigate postural responses to visual field motion in college athletes having sustained mTBI; they documented balance deficits induced by visual field motion 30 days post-injury, which was interpreted as a residual sensory integration dysfunction in concussed individuals. Studies on balance difficulties following mTBI in children are scarce. Some studies have shown deficits in balance ability in children following a mTBI (Gagnon, Forget, Sullivan, & Friedman, 1998; Gagnon et al., 2004a; Guskiewicz, Perrin, & Gansneder, 1996). To our knowledge, the influence of vision in

postural control following mTBI has not been previously investigated in children following mTBI, while concurrently evaluating the evolution of these characteristics up to one year post-injury. It would nonetheless be important to be investigated given that traumatic brain injury (TBI) is a leading cause of disability in children (Katz-Leurer, Rotem, Keren, & Meyer, 2009): indeed, in the USA, the reported annual incidence of mild TBI in the child population (aged 5-14) in 1998-2000 was 733.3 per 100 000 (Bazarian et al., 2005). Additionally, despite normal structural neuroradiological results in mTBI, several physical, cognitive and emotional post-concussion symptoms are frequently reported in the first 3 months post-injury (Mittenberg, Wittner, & Miller, 1997).

Objectives of the Thesis

This manuscript is divided into two parts and includes four studies looking at the relative weight of vision in different populations using a methodologically solid, powerful, ecological, and fully immersive experimental paradigm, the *Virtual Tunnel Paradigm*, that shall be detailed in the next section. Specific hypotheses for each of the 4 studies will be enunciated thereafter.

PART A: The general objective of this section is to document visually-driven postural regulation as a function of age, that is, throughout the life-span (5 to 85 years of age) in healthy individual, and as a function of velocity of optic flow stimulation. Hence, *Chapter 1* addresses how typically developing children of different ages (5 to 25 years of age) use different velocities of dynamic visual cues to regulate posture, and *Chapter 2* completes *Chapter 1* as it looks at the visually-driven postural regulation as a function of age and optic flow velocity in young, middle-aged and older healthy adults (25 to 85 years of age).

PART B: The general objective of this section is to explore how diffuse alterations to the CNS, either of an innate nature (autism) or an acquired one (mTBI) influence visually-driven postural control as a function of dynamic visual stimulation velocity in a group of young individuals with high-functioning autism and in another group of young individuals with mild

traumatic brain injury. Thus, *Chapter 3* focuses on the way that young individuals (12 to 33 years of age) with atypical development (high-functioning autism) react to dynamic visual stimuli at different ages and velocities of the visual stimuli. *Chapter 4* consists in a short report of preliminary results concerning the visually-driven postural control alterations in young individuals (9 to 18 years of age) having sustained a mild traumatic brain injury, as a function of visual stimulation velocity, severity of post-traumatic symptoms, and as a function of time post-injury (2 weeks, 12 weeks, and 12 months post-injury).

The Virtual Tunnel Paradigm

The classical Lee and Aronson's (1974) swinging-room paradigm has been used by several researchers to investigate the development of postural reactivity. In this seminal study, a room was manually manipulated around standing participants in the anterior-posterior direction, thereby inducing optic flow, after which they observed strong postural reactions and adjustments. Experimental paradigms have since become more sophisticated (see below). 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 (Piponnier et al. 2009, 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 postural measures 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. Similarly, Slobounov et al. (2006) were able to induce vection and actual postural instability in standing humans by using a VR Visual Field Motion in 3D with 3 walls containing black and white stripped pattern moving at different frequencies (0.30 to 0.60 Hz). Finally, a study by Faubert and Allard, (2004) using a VR paradigm administering sinusoidal stimulation (waves virtually moving on the floor made of a checkerboard pattern) using the CAVE system (the same as used in our studies) were successful at inducing important postural reactivity in healthy individuals.

Stimuli

The rationale for creating a moving fully immersive visual stimulus was inspired by Lee and Aronson's Swinging Room Paradigm, by the previously mentioned studies, and by the fact that observing a moving environment in which amplitude and velocity are greater than those produced by spontaneous body sway creates the illusion of moving through the environment, or that the environment itself is moving. This illusion of self-motion is called *vection* and elicits a corresponding compensatory postural response intended to reduce observed changes in optic flow (Piponnier, Hanssens, & Faubert, 2009). In an effort to come up with an ecological, fully immersive, dynamic, and powerful visual stimulation to study visually-dependant postural reactivity, our main stimulus consisted of a tunnel made of alternating black and white squares forming a checkerboard pattern where each square was scaled for linear perspective and was $1m^2$ in dimension; 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 moved in the anterior–posterior direction obeying a sinusoidal translation motion oscillating with the following function: $A = 2sin (2 \times pi \times f \times t)$, where A represents amplitude, 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). The tunnel's virtual length was 20 m and its diameter 3 m; both of these dimensions remained constant across all trials.

The association of the shape (cylinder), texture (checkerboard pattern), movement, 3D character, and linear perspective of the tunnel (see Figure 2) provided a strong and ecological optic flow stimulation to the peripheral visual field, to which, as was mentioned earlier, the visual system is very sensitive and responsive with respect to the control of stance.
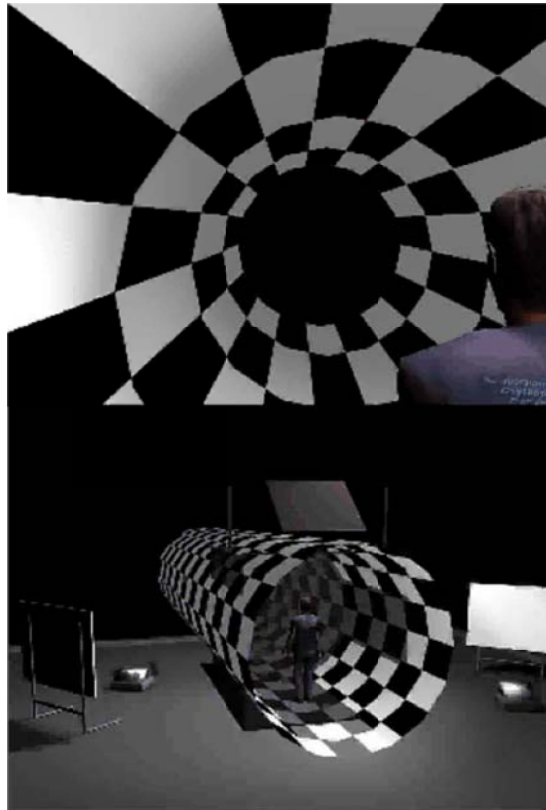
I-Figure 2. The Virtual Tunnel.

<u>Apparatus</u>

The experiments were conducted in a CAVE (Cave Automatic Virtual Environment; FakespaceTM). The CAVE is a large 8 x 8 x 8 feet theatre situated within a larger room that allows individuals to be immersed in 3D virtual environments and 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). It consists of three projection walls and an epoxy floor (Figure 3) onto which images generated by synchronized projectors are back-projected with the help of mirrors; the resolution of each surface image was 1280 x 1024 pixels and was generated by Marquee Ultra 8500 projectors. Two images, one for each eye, with spatial disparities are displayed and three-dimensional vision is made possible by the use of stereo shutter goggles (Crystal Eyes from the StereoGraphics Corporation). Indeed, three-dimensional (stereoscopic) vision, being the result of the computation of two different images (one from each eye) by the brain, wearing stereoscopic goggles allows for the alternating occlusion of the left and right eyes at a high frequency (96 Hz). This occlusion is synchronized with the projection frequency of the images on the screens, resulting in a three-dimensional perception of the environment. A magnetic motion tracking system placed on the goggles tracks and records a person's position and orientation in space at a high frequency (64 Hz). This allows for the images to be updated in real time to maintain the true viewing perspective of the observer (Piponnier et al., 2009).
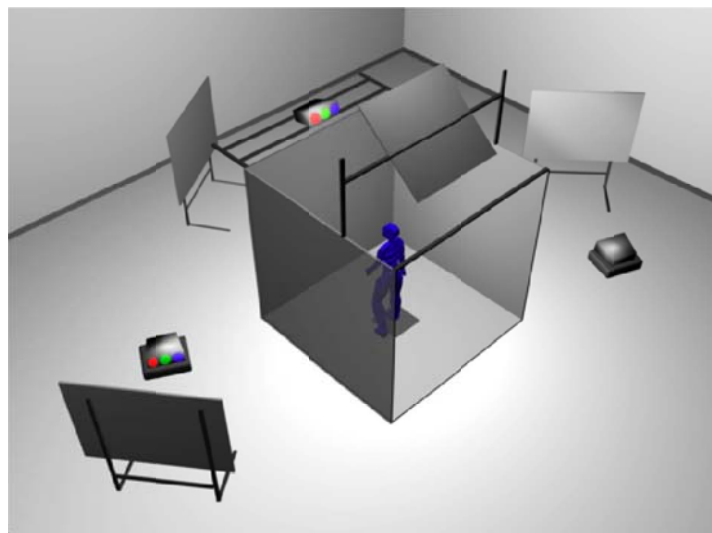
I-Figure 3. The Cave Automatic Virtual Environment (CAVE).

<u>Experimental Design and Procedures</u>

In our experimental design, we used two types of conditions: 1) control conditions, and 2) dynamic conditions. In the <u>Dynamic Conditions</u>, the virtual tunnel obeyed a translational sinusoidal motion pattern at three different frequencies: 0.125 Hz, 0.25 Hz, 0.50 Hz; these frequencies were found to be the ones inducing the most postural reactivity in healthy young subjects (Hanssens, Allard, Giraudet, & Faubert, 2013) and the choice of a sinusoidal stimulus allowed for the repeated administration of optic flow stimulation in order to maximise the number of postural behavior data points, which were about 3600 per trial (Faubert & Allard, 2004); note that in the latter study, this type of stimulus (sinusoidal) induced important postural sway.

Two control conditions were included in order to isolate the contribution of dynamic optic flow to postural reactivity from that due to spontaneous sway and postural instability: 1) the <u>Static Tunnel Condition</u>, where participants had to quietly stand while staring at the center of the virtual tunnel in a static state during two 68 s trials; the only variable differentiating this condition from the dynamic tunnel one is the motion of the stimulus since the structure and texture of the stimulus are identical in both conditions, therefore, this allowed us to isolate the contribution of the dynamic character of the visual stimulation to posture control; 2) the <u>Eyes Closed Condition</u> where participants maintained a standing position but had their eyes closed during two 68 s trials, therefore documenting postural behavior in the total absence of visual stimulation.

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 motion 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 in order to minimize the use of individual strategies from the limbs to maintain posture and help maximize the effect of the stimulation. For all of the conditions, they were asked to stare at a red dot located at the horizon.

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. 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, younger children and older adults were authorized to rest (if needed) after three dynamic trials since for these age groups, the 9 dynamic trials were divided into 3 separate testing episodes. 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.

Measures of Postural Behavior

Prior to testing, precise calibration of the motion sensor system was done by displacing the sensor every foot in x, z and y coordinates and registering the recording position; a calibration function was implemented to correct for mismatches between recorded position and real sensor position (Faubert & Allard, 2004). Moreover, it that same device, 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.

Two measures reflecting distinct visuo-dependant behavior were used and motion data points were sampled at a rate of 64Hz:

1) Body Sway or BS, (Faubert & Allard, 2004; Minshew et al., 2004; Schmuckler, 1997; Sparto et al., 2006). This measure represents an antero-posterior displacement in degrees of angle specific to the tunnel's stimulation frequency, and it reflects the observer's

capacity to react to, and synchronize with, a given stimulus. That is, it represents the average body amplitude of a person's movement over a period of 68s (trial duration) at either 0.125Hz, 0.25Hz, or 0.50Hz (Figure 4).
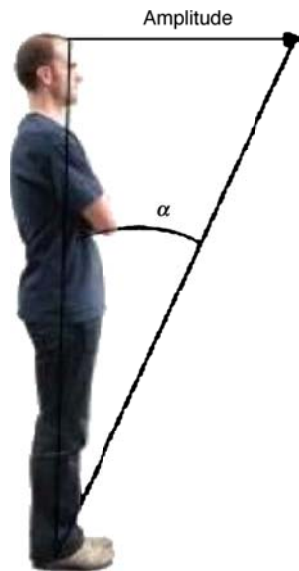
I-Figure 4. Body Sway: Average angular displacement of a person during a 68s trial.

The BS 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). 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). Also, 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 participant's height into account, linear displacement measures (BS in

cm) were converted into 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". Note that in *Chapter 1*, the BS measure was present for both of the Static and Eyes Closed conditions for each of the stimulation frequencies (i.e., 0.125Hz, 0.25Hz, 0.50Hz); this can seem counter-intuitive a priori given that no dynamic stimulation is administered, however, the body spontaneously oscillates at different frequencies, even in the absence of specific stimulation; it is therefore possible to obtain a measure of Body Sway for each of the desired frequencies by running spectral analyses (FFT). Thus, in this case, BS does not represent synchronisation to stimulus but rather an average spontaneous sway in the anterior-posterior direction during a 68s trial at the specified frequency.

2) <u>Postural Perturbations</u> (PP) or vRMS is a measure of a body's velocity root mean squared in cm/s (in the first study on development) or in deg/s (in the 3 other studies) obtained for all frequencies except that of the stimulus; it indicates the total displacements of a person as a function of time 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) that is not directly driven by the frequency of the visual stimulus (Greffou et al., 2011; Greffou, Bertone, Hanssens, & Faubert, 2008). PP was used in order to quantify possible postural perturbations induced by the visual stimuli, so as to 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.

Thesis's Research Hypotheses

PART A:

H1. In the light of the scientific literature previously mentioned, it was hypothesized that in the first study, healthy children and adolescents would demonstrate higher amounts of postural reactivity (for both BS and PP) compared to the young adults, since children seem to rely more heavily on visual input for postural control than young adults do (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; Grasso et al., 1998). Furthermore, it was hypothesized that the amount of BS would decrease as the age increased. Regarding the vRMS measure, it was hypothesized that children would show greater vRMS values compared to adults. In essence, postural stability was expected to increase with age. Moreover, postural reactivity of children was expected to be even more elevated at higher stimulation frequencies as infants and young children seem to use both high and low frequencies for postural control compared to adults who rather react to lower frequencies (Delorme, Frigon, and Lagacé, 1989; Bai, 1991; Schmuckler, 1997). No effects of age were expected for the control conditions.

H2. This higher amount of postural reactivity and the over-reliance on visual input present in children and adolescents were expected to return later on in life, potentially around 40-50 years of age and significantly return after 60 years of age. We also hypothesized that the highest oscillation frequency of the virtual tunnel would induce the greatest reactivity in older adults since this would require faster processing and integration of sensory input, and potentially create a saturation of the postural control system. Conversely, in conditions where dynamic visual input is absent (Static Tunnel or Eyes Closed), differences in postural perturbations across different age groups should be smaller, as they consist of less challenging tasks for the postural system.

PART B:

H3. It was expected that children with a innate neurobiological differences, i.e., autism, would show altered postural regulation since visual information processing is involved in several visually-contingent behaviors, including maintaining posture, or balance and is atypical in autism. Either hyper or hypo postural reactivity compared to controls was expected, since Gepner et al. (1995) reported a hypo-reactivity to an optic flow stimulus, and Molloy et al. (2003) demonstrated an over-reliance on visual input for maintaining balance in the autism/ASD group.

H4. It was hypothesized that children with an acquired alteration to the CNS, having sustained mTBI, would show more postural reactivity (BS and PP) compared to their controls given that an over-reliance on visual input for postural regulation was reported in adults following mTBI (Rubin, Woolley, Dailey, & Goebel, 1995), even up to 30 days post-injury (Slobounov et al., 2006). Furthermore, this over-reliance on vision to control posture following mTBI was expected to last at least 3 months post-injury since studies conducted on balance abilities of children following mTBI have shown deficits up to 12 weeks post-injury (Gagnon, Forget, Sullivan, & Friedman, 1998; Gagnon et al., 2004a; Guskiewicz, Perrin, & Gansneder, 1996). Lastly, elevated initial total score of post-traumatic symptoms in mTBI participants was believed to predictive of postural anomalies.

PART A: Chapter 1-Article 1

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

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Abstract

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.

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 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 ($n = 6$), 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.
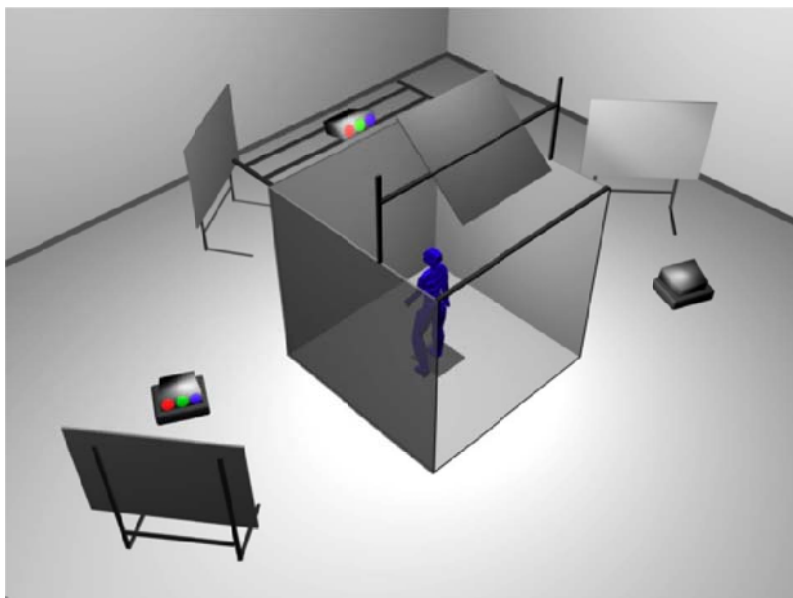
C1-Figure 1. The CAVE is an 8 x 8 x 8 foot room that includes three walls (one frontal and two lateral) and a floor that all serve as surfaces for image projection.

Apparatus

Postural reactivity to visual information was assessed using a fully immersive virtual environment or the CAVE system (Fakespace™). The CAVE is an 8 x 8 x 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 x 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: $A = 2\sin(2 \times pi \times f \times t)$, where A represents amplitude, 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.
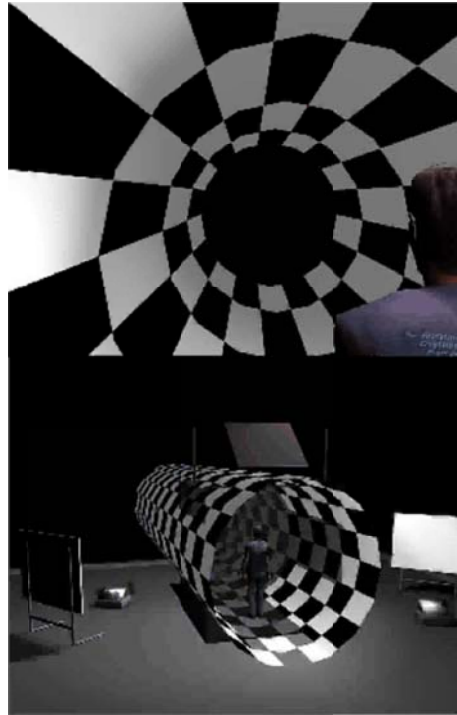
C1-Figure 2. The Virtual Tunnel Paradigm. For demos, go to http://vision.opto.umontreal.ca

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) x 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).
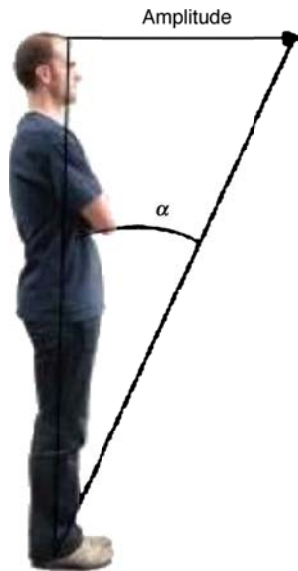
C1-Figure 3. Angular displacement of a person.

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 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.

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) x 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 x 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.
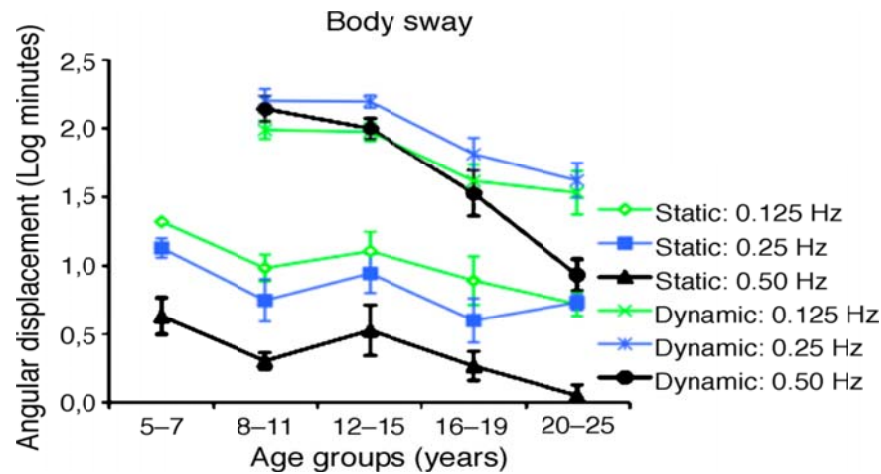
C1-Figure 4. BS means (log minutes) as a function of age group and translation frequency. *SEM* are shown for each age group.

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) x 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 x 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

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oscillation. As is obvious from Figure 5, the Oscillation Frequency condition was highly significant, $F(3, 57) = 20.0730$, $p = 0.0001$.
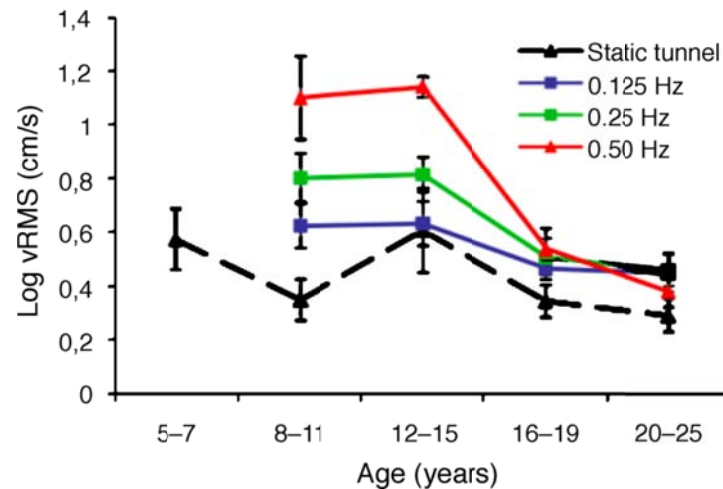
C1-Figure 5. vRMS in log (cm/s) as a function of age and oscillation frequency. SEM are shown for each age group.

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, Schnöer, Giese, & Gielen, 1994; Giese, Dijkstra, Schnöer, & Gielen, 1996; Schnöer, 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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PART A: Chapter 2-Article 2

Visually driven postural reactivity in healthy aging

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Abstract

The objective of this study was to investigate the effect of aging on visually driven postural regulation in healthy adults of different ages (25 to 85 years of age). Fifty-nine healthy participants were divided into 3 age groups (25–44 years, 45–55 years, 60-85 years) and were asked to stand within a virtual tunnel that oscillated in an anterior–posterior fashion at three different frequencies (0.125 Hz, 0.25 Hz, and 0.5 Hz). Body sway (BS) and Postural Perturbations (PP or velocity root mean squared-vRMS) were measured. BS and PP augmented linearly with age for all of the temporal frequency conditions except one (BS at 0.25 Hz was stable as a function of age). The finding that both BS and PP significantly augmented with age over the majority of conditions suggests that the over-reliance on visual information that was shown to be present in early childhood (Greffou et al., 2008) returns and that significant sensorimotor changes occur after 60 years of age within the context of feedback control of posture.

Keywords: Posture, visual flow, sensorimotor aging, virtual environment, body sway, postural perturbations.

Introduction

Humans use three different afferent sensory systems to regulate their posture; the somatosensory, the vestibular and the visual systems (Peterka & Benolken, 1995; Nolan, Grigorenko & Thorstensson, 2005). However, the relative weight of each one of these senses with regards to postural control appears to vary as a function of age. Indeed, numerous studies have shown that children rely more heavily on visual input to regulate their posture than adults (Greffou, Bertone, Hanssens, & Faubert, 2008). Scarcer are the studies that have looked at the contribution of visual input to postural regulation in older adults, but generally, these studies have reported a return of the over-reliance on vision in postural control at more advanced ages. For example, Hytonen, Pyykko, Aalto, & Starck, (1993) have assessed the sway velocity of 6

to 90 year-old healthy participants with both eyes open and eyes closed and found that the amount of sway showed a U-shaped curve, where the visual system was of most importance for balance control in children and in older adults. Other studies have shown that older adults were generally more destabilized by optical flow stimuli than younger adults (Sundermier, Woollacott, Jensen, & Moore, 1996; Wade, Lindquist, Taylor, & Treat-Jacobson, 1995). Moreover, Era, et al., (2006)'s study has shown that a deterioration in balance function (as measured by increased sway on a force platform with eyes open) starts around middle-age and further accelerates at about 60 years upwards. In a study by Hytonen (1993), the greatest postural stability was present around 50 years of age and the visual system was found to be of most importance for balance control in their eldest participants (when comparing performances on eyes open and eyes closed). Finally, Poulain & Giraudet, (2008) used a virtual reality environment to assess if 44 to 60 year-old individuals would significantly differ from younger adults as it pertains to postural behavior in response to visual stimulation; they found that middle-aged participants showed greater visual sensitivity in posture control (i.e., greater instability) starting at age 44.

Although these studies are very interesting, we still lack a good understanding of the role of optic flow on posture control. Indeed, the abovementioned studies have demonstrated a return to visual dependence in balance control at more advanced ages, but their research paradigms did not allow for a precise control over variables defining the visual stimulation, such as velocity (e.g., oscillation frequency), nor for precise measures of body movement as a function of the precise characteristics of the stimulation. Additionally, the age ranges chosen often excluded middle-aged individuals, which does not fully allow for the understanding of visually-dependant postural regulation across life-span. After having studied visuo-dependant postural reactivity in children (5 to 25 years of age) using the Virtual Tunnel Paradigm (Greffou et al., 2008), a fully immersive virtual visual environment, the present study was intended to investigate young, middle-aged, and older adults (25 years to 85 years) in the same conditions. In doing so, we wanted to learn about the evolution of postural behavior in

response to different velocities of the visual environment and to better understand the relative weight of vision in postural regulation as a function of age.

Here, postural reactivity was measured using two variables: Body Sway and Postural Perturbations (Greffou et al., 2011). We hypothesized that postural reactivity to visual dynamic scenes would augment with increasing age and that the over-reliance on vision for postural control evidenced in children would commence around 40-50 years of age and significantly return after 60 years of age. We also hypothesized that the highest oscillation frequency of the virtual tunnel would induce the greatest reactivity in older adults since this would require faster processing and integration of sensory input, and potentially create a saturation of the postural control system. Conversely, in conditions where dynamic visual input is absent (Static Tunnel or Eyes Closed), differences in postural perturbations across different age groups should be smaller, as they consist of less challenging tasks for the postural system.

Methods

Participants

Fifty-nine healthy adults with no history of neurological disease, orthopedic problems, or major health problems voluntarily participated in this study. They all had normal or corrected-to-normal vision (for both eyes) and a normal score on a screening test for cognitive impairments (more details in the *Procedure* section). They were categorized according to 3 age groups: the young group (25-44 years; $n = 19$), the middle-aged group (45-55 years; $n = 12$), and the elderly group (60-85 years; $n = 28$).

Apparatus

Postural reactivity in response to visual information was captured with the help of a fully immersive virtual environment (the CAVE system; Fakespace™). The CAVE is an 8 x 8 x 8 feet room made of three canvas walls (one frontal and two laterals) and an epoxy floor; images are projected onto the surface of these walls (Figure 1). The resolution of each surface image was 1280x1024 pixels and was generated by Marquee Ultra 8500 projectors. The CAVE is under the control of a computer called SGI ONYX 3200 (two Infinite Reality graphics cards), and is equipped with a magnetic motion tracker system (Flock-of-Birds) that measures postural reactivity by monitoring body movement. Magnetic motion sensors were located on stereoscopic goggles polarized at 90° named Crystal Eyes from the StereoGraphics Corporation. For more information on the CAVE system, please visit the following website: http://vision.opto.umontreal.ca/english/technologies/Icube_cave.html.
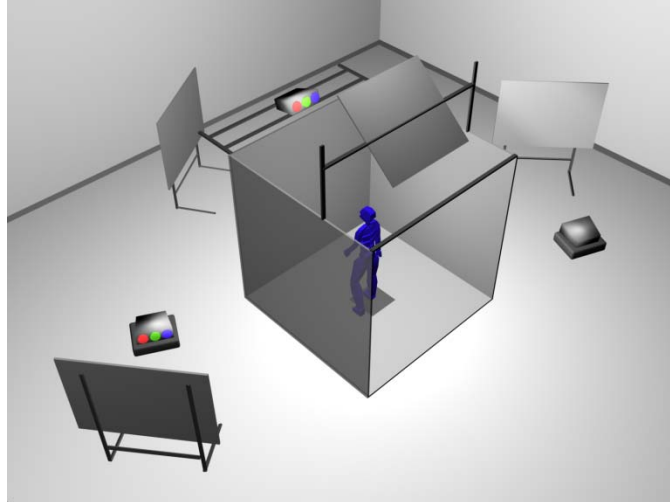
C2-Figure 1. The CAVE is an 8 x 8 x 8 foot room which includes three walls (one frontal and two lateral) and a floor that all serve as surfaces for image projection.

Procedure

After signing the consent form, participants' visual acuity was assessed using a Snellen eye-chart where they had to have 20/20 (with corrective lenses or without); they also had to pass a screening test for stereoscopic vision (Randot Stereo Test-Precision Vision®) and had to have no history of ocular disease to be included in the study. Participants also underwent a brief examination of their cognitive status using the Mini-Mental State Examination (the cut-off score was 24/30). They then headed to the CAVE and were familiarized with the virtual environment. They were asked to wear stereoscopic goggles, which allowed them to perceive the visual environment in 3D and allowed for the tracking of their motion with the magnetic sensors. Participants had to position themselves 1.50 m away from the CAVE' s central wall with their shoes off, feet together, and arms crossed. This position was chosen in order to maximize the effect of the visual stimulation by augmenting postural perturbations. For all of the testing conditions, participants were asked to stare at a red dot located at the horizon. The tasks were passive in that behavioral information was recorded as the participants simply stood in the virtual reality environment while presented with the visual stimulation.

A trial was considered to be non-completed whenever a participant: lost balance and stepped twice, he or she could not remain standing during the trial, or asked for the trial to be stopped. If a participant was unable to complete 2 out of the 3 dynamic trials for a given oscillation frequency, their data was excluded from statistical analyses; note that this happened for none of the adult participants in this study.

Experimental paradigm

The *Virtual Tunnel Paradigm* was used to assess postural reactivity (Greffou et al., 2012; Greffou et al., 2008; Piponnier, Hanssens, & Faubert, 2009). The tunnel's inner texture consisted in a checkerboard pattern where each square was scaled for linear perspective and was 1m2 in dimension (Figure 2). The luminance of the white squares was 47 cd/m2 and that of the black squares 0.52 cd/m2 (98% Michelson contrast). The tunnel's virtual length

measured 20 m and its diameter 3 m. Both of the luminance and the tunnel's dimensions remained constant across all trials.

Two types of conditions were used in this study: dynamic tunnel conditions and control conditions. In the dynamic tunnel conditions, the tunnel oscillated in an anterior–posterior way obeying a sinusoidal translation function: $A = 2\sin(2 \times \mathrm{pi} \times f \times t)$, where A represents amplitude, t represents time in seconds, and f represents frequency (0.125 Hz ($T = 8$ s); 0.25 Hz ($T = 4$ s); and 0.5 Hz ($T = 2$ s)). This choice of frequencies was made as it has been demonstrated that when virtual visual scenes oscillate at frequencies lower than 0.40 to 0.50 Hz, postural sway is maximal (Hanssens, Allard, Giraudet, & Faubert, 2013). The amplitude of the tunnel's translation was 2 m during all of the dynamic trials (a peak-to-peak amplitude of 4 m). Participants performed 3 trials of 68 s for each one of the oscillation frequencies. The 9 trials were presented in a pseudo-random order where the initial frequency was randomly selected; moreover, a frequency was not presented again until each of the two other frequencies were presented. The inter-trial interval was 5 s.

Two control conditions were added in order to isolate the contribution of dynamic optic flow to postural reactivity due to spontaneous sway, namely: *static tunnel* and *eyes closed*. During the *static tunnel* condition, participants had to stare at a red dot at the horizon while presented with the virtual tunnel in a static state (0 Hz) during two 68 s trials (separated by a 5 s interval). In this condition, the structure and texture of the tunnel is identical to that in the *dynamic conditions*; hence, this allows for the isolation of the effect of visual motion on posture by comparing the effect of the tunnel's motion versus the effect of the mere presence of the static tunnel. In the *eyes closed condition*, participants were asked to position themselves just like in the dynamic or static tunnel conditions but to close their eyes during two 68 s trials (again, separated by a 5 s interval). This condition allowed for the comparison of postural behavior in the absence of any visual input versus the presence thereof.
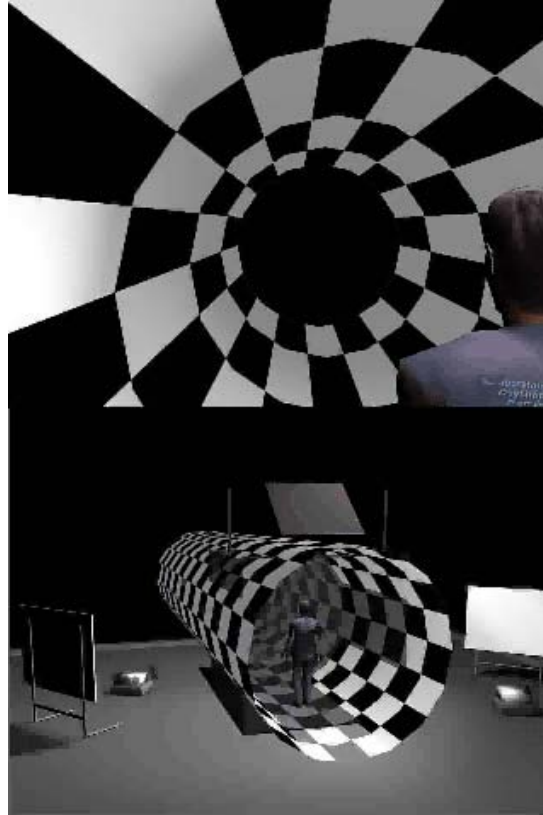
C2-Figure 2. The Virtual Tunnel Paradigm.

All in all, participants performed thirteen 68-s trials in the following 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 and stepped twice; (2) could not remain standing; (3) asked for the trial to be stopped. Whenever a participant was unable to complete 2 out of the 3 dynamic trials for a given oscillation frequency, his/her data was excluded from statistical analyses.

<u>Behavioral measures</u>

Changes in posture were monitored with two measures: Body Sway and Postural Perturbations (Greffou et al., 2011). Motion data points were sampled at a rate of 64 Hz.

Body Sway (BS) is defined as the average anterior–posterior displacement of a participant at a given translation frequency during a complete trial (Greffou et al., 2011); therefore this measure was only available for dynamic conditions. To account for individual differences in height, we used angular displacement in minutes of angles as the unit for Body Sway in order to account for the relative magnitude of displacement. Postural Perturbations (PP) was used in order to quantify perturbations induced by the visual stimuli (for dynamic and static conditions) or to spontaneous movements during the eyes closed condition. PP consists of the root mean squared of the total body velocity (vRMS) in the anterior–posterior ("z axis") and medial-lateral ("x axis") planes in minutes of angles per second.

The PP measure differs from the BS one in that PP is not computed relative to a single specific frequency but rather reflects body velocity at all frequencies. In the present study, we calculated the PP in the same way as Greffou et al., (2008), except that we have converted cm/s into minutes of angle/s; once again, this was done to account for the various heights of participants and their relative displacement (Greffou et al., 2011).

Results

Body Sway

Body Sway results are shown in Figure 3. In order to probe differences in Body Sway (BS) between the 3 age groups whilst accounting for stimulus velocity, a 3 (Age Groups) x 3 (Oscillation Frequency) mixed factorial analysis of variance (ANOVA) was conducted for the dynamic conditions. This ANOVA revealed a significant main effect of age group, $F(2, 56) = 5.273$, $p = 0.008$, more precisely, Tukey HSD multiple comparisons revealed that the elderly

group showed significantly more BS than the young group ($p = 0.013$) and more BS than the middle-aged group, although statistical significance was not quite reached ($p = 0.062$). No significant differences were evidenced between the young and the middle-aged group. Additionally, a significant main effect of oscillation frequency was found, $F(2, 112) = 83.781$, $p = 0.000$, as well as a significant Age Group x Oscillation Frequency interaction, $F(4, 112) = 3.593$, $p = 0.009$; more precisely, pairwise comparisons using Bonferroni corrections revealed that BS was more elevated in the elderly group compared to the young group for the slowest and fastest two frequencies (0.125Hz, $p = 0.003$; and 0.50Hz, $p = 0.005$) and was also more elevated than that of the middle-aged at the fastest frequency 0.50Hz, but this was not statistically significant ($p = 0.078$).
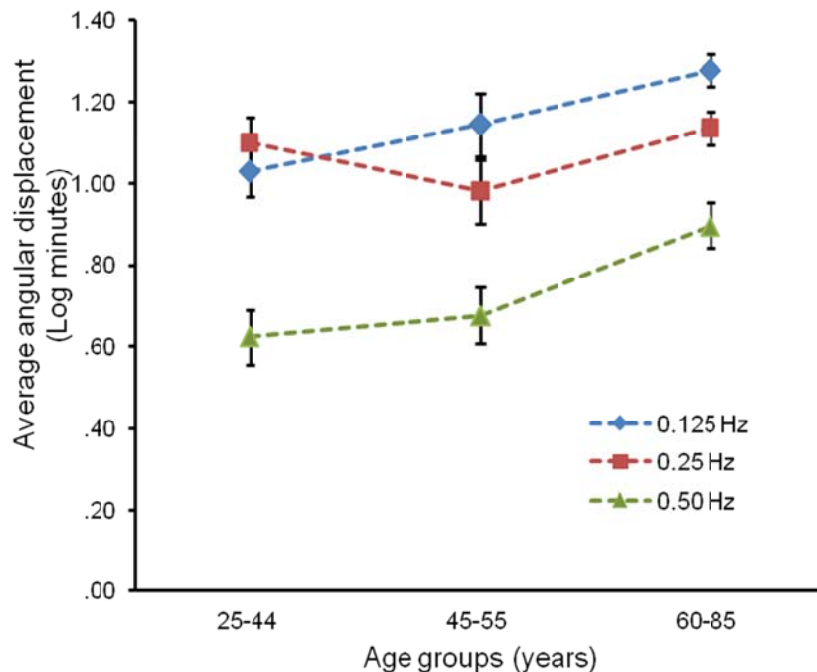
C2-Figure 3. Body Sway means (log minutes) as a function of age group and oscillation frequency. *SEM* shown for each age group.
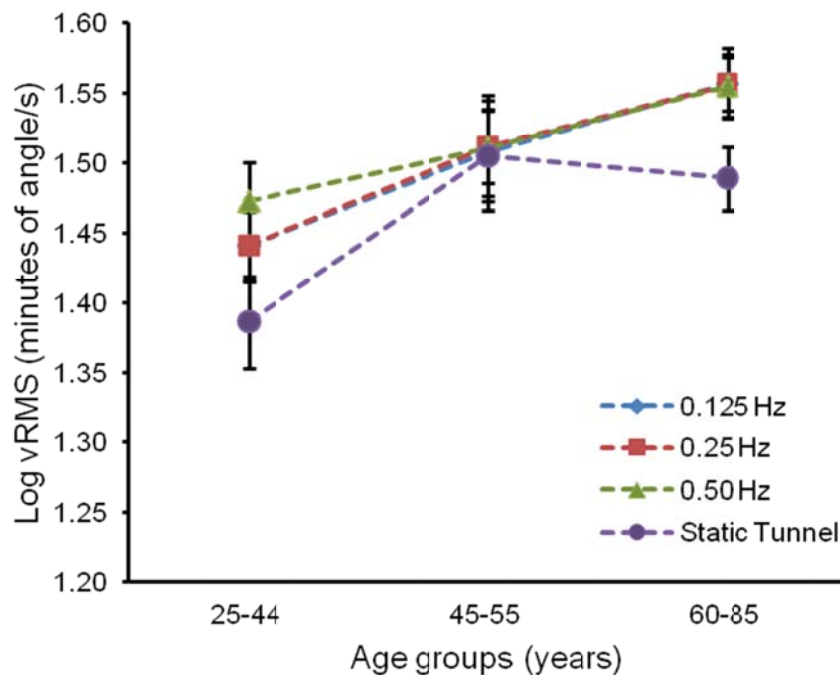
Postural Perturbations

Postural Perturbations results are shown in Figure 4. As was done for BS, a 3 (Age Groups) x 3 (Oscillation Frequency) mixed factorial analysis of variance (ANOVA) was ran for the PP measure for the dynamic conditions. Akin to the BS results, there was a significant main effect of Age Group, $F(2, 56) = 6.837$, $p = 0.002$, more precisely, Tukey HSD multiple comparisons revealed that the elderly group showed significantly more PP than the young group ($p = 0.001$). However, contrary to the BS results, there was no significant main effect of Oscillation Frequency nor a significant Age Group x Oscillation Frequency interaction.

In order to investigate whether PP group differences existed in the absence of dynamic visual stimuli, a one-way ANOVA was conducted for the Static Condition (note that no analyses are reported for the eyes closed condition as regression analyses showed no significant differences between the static and the eyes closed conditions). Results of the ANOVA showed a significant main effect of Age Group, $F(2, 58) = 4.706$, $p = 0.013$; Tukey HSD multiple comparisons revealed that both the middle-aged and the elderly groups demonstrated more PP compared to the young group (respectively $p = 0.036$ and $p = 0.023$) in the absence of dynamic visual stimuli.

Although the group differences were more important during the dynamic conditions compared to the static condition (respectively $p = 0.002$ vs. $p = 0.013$), it remained unclear whether it was predominantly the dynamic character of the visual stimuli that explained the group differences or if it were rather simply due to spontaneous sway. Hence, an analysis of covariance (ANCOVA) was conducted with the static condition's PP values being the co-variable. This allowed us to probe whether group differences existed even after controlling for spontaneous sway. As was expected, the ANCOVA revealed a significant main effect of Age Group, $F(2, 55) = 3.733$, $p = 0.030$; pairwise comparisons using Bonferroni corrections showed that the main effect of age was driven by the difference between the elderly group and the young group, the latter having exhibited less PP than the former ($p = 0.05$). Contrary to

what was hypothesized, there was no significant main effect of Oscillation Frequency nor a significant Age Group x Oscillation Frequency interaction for the PP measure. Taken together, these results suggest that, on average, participants above the age of 60 years had more postural perturbations in response to dynamic visual stimulation than the young participants (25-44 years of age), even when controlling for the differences due to spontaneous sway, and regardless of the oscillation frequency of the stimulus.

C2-Figure 4. Postural Perturbations in Log vRMS (minutes/s) as a function of age and oscillation frequency. *SEM* are shown for each age group.

Discussion

The objective of this study was to elaborate on our previous findings in children by investigating on the effect of aging on visually driven postural regulation in healthy adults of different ages (25 to 85 years of age) using a fully immersive virtual reality system. The virtual tunnel moved at three different velocities (0.125 Hz, 0.25 Hz, and 0.5 Hz) and two measures were obtained: Body sway (BS) and Postural Perturbations (PP). Results showed that both BS and PP augmented linearly with age for all of the temporal frequency conditions except one (BS at 0.25 Hz was stable as a function of age). The finding that both BS and PP significantly increased with age over the majority of conditions suggests that the over-reliance on visual information that was shown to be present in early childhood and that diminishes in early adulthood (Greffou et al., 2008), returns later on in life, suggesting that important sensorimotor changes occur after 60 years of age with regards to feedback control of posture.

Given that the nature of our stimuli was fully immersive, passive (very little cognitive load), and highly contrasted, it is unlikely that the differences between the elderly and the young groups were driven by changes in attention allocation like was suggested by some (Mahboobin, Loughlin, & Redfern, 2006). Likewise, although changes in the use of muscle synergies during postural regulation have been reported with age (Woollacott, Inglin, & Manchester, 1988), the chosen experimental position in our experiment (feet together, arms crossed, straight head) minimized the use of individual strategies.

The finding that both of the middle-aged and the elderly groups showed greater PP than the young group in the Static Tunnel condition could be explained by age-related changes (decrements) of the following nature: neuromuscular (Woollacott et al., 1988), vestibular (Furman, & Cass, 2003), and somatosensory (Qiu et al., 2012). Although these kinds of changes may be sufficient to explain age-differences in passive quiet standing (either with eyes closed or eyes open), they are not sufficient to explain the age-differences observed when the tunnel was dynamic. Indeed, the ANCOVA revealed that the differences between the

elderly group and the young group on the PP measure was still present after controlling for spontaneous sway in the absence of dynamic visual stimulation (Static Tunnel), regardless of stimulation frequency. One could think that this could be explained by the fact that visual perception changes in the elderly (i.e., stimuli are misperceived or magnified), however, this is unlikely to be the case for the following reason: on the BS measure, the older adults exhibited more sway at the very frequencies of the stimulation, thereby showing increased synchronized postural responses to each of the stimulation frequencies. In other words, it is the magnitude of the already-existing postural response (in the young ones) that has increased with age. It is probable that the increase in the magnitude of postural response is contingent on stimulus complexity: a review on the visual deficits related to aging by Faubert (2002) has argued that age-related changes in visual perception seems to rather be a consequence of stimuli complexity (computational load or complexity of neural network) than a consequence of the impairment of specific visual systems. Linking this idea to our findings, in the Static Tunnel condition, the stimulus is mainly luminance and depth defined, whereas in the Dynamic Tunnel conditions, an extra degree of complexity is added by introducing the *motion* variable. The fact that the complexity of the stimuli to be processed and integrated by the central nervous system augmented in the dynamic compared to the static conditions may have more importantly challenged the postural control system of the older participants, thereby creating a saturation of this system and, consequently, the emergence of sub-optimal patterns of motor output (greater PP and BS). The evidence that having to maintain a simple upright stance somehow interacts with dynamic scene processing, making the task more complex, has been shown with a learning paradigm (Faubert & Sidebottom, 2012). In this study, we compared professional athletes that were either in a standing or sitting position while they were learning to process a complex dynamic scene task. What we found was that the two groups differed remarkably in their learning functions where the standing group were improving at the task at a much slower rate than their sitting counterparts. This was quite surprising given that these high-level athletes are in fact much more proficient at learning this dynamic scene task as compared to non-athletes (Faubert, 2013) and supports the notion that neural circuits required to process dynamic scenes, and the mechanisms necessary for maintaining upright quiet stance interact in a significant way.

In the same line of ideas, although some sensory systems may individually undergo age-related losses (e.g., vestibular system), multi-sensory integration has often been shown to become less efficient with age (for a review, see Mozolic, Hugenschmidt, Peiffer, & Laurienti, 2012). As was mentioned in the introduction, three sensory systems are utilized for postural regulation: the vestibular, the somatosensory, and the visual one; the complex integration of the afferents from each of these sensory modalities within the central nervous system is then required and appropriate motor commands and efferents have to be generated accordingly. It can be hypothesized from our findings that starting from 45 years of age, the over-reliance on vision observed in children returns and even more so after age 60. This could be due to the fact that the visual system is a more blue-printed system than the other ones, making it the default system in the face of sensorimotor difficulties. This argument is consistent with our previous findings where visual input was disproportionately influential compared to proprioceptive and vestibular inputs on postural regulation in younger children until reaching adult-like levels around 16-19 years of age (Greffou et al., 2008).

Conclusion

We believe that the powerful stimulation pertaining to the fully immersive visual environment used in this study combined to the wide range of ages that were investigated has helped us gather strong evidence that critical phases for sensorimotor changes, notably the over-reliance on vision in postural control, is not only present in early childhood but also starts reappearing in middle-age and even more so at around 60 years of age. These findings are important as they can have important implications for prevention of falls in the elderly (e.g. by guiding better management of living commodities; escalators, etc…), whose prevalence is elevated and highly costly to society (Rubenstein, 2006; Stevens, Corso, Finkelstein, & Miller, 2006), and for the practice of sports (e.g. velocity sports). Finally, the population tested here consisted of healthy high-functioning aging individuals, which is not fully representative of the typical aging population. In the future, it would be interesting to study how experience/expertise in dealing with fast moving visual scenes (e.g., experienced drivers or ex-athletes) influences visually-driven postural regulation in aging individuals.

Acknowledgments

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PART B: Chapter 3-Article 3

Atypical postural reactivity in autism is contingent on development and visual environment: A fully immersive virtual reality study

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Abstract

Although atypical motor behaviors have been associated with autism, investigations regarding their possible origins are scarce. This study assessed the visual and vestibular components involved in atypical postural reactivity in autism. Postural reactivity and stability were measured for younger (12–15 years) and older (16–33 years) autistic participants in response to a virtual tunnel oscillating at different frequencies. At the highest oscillation frequency, younger autistic participants showed significantly less instability compared to younger typically developing participants; no such group differences were evidenced for older participants. Additionally, no significant differences in postural behavior were found between all 4 groups when presented with static or without visual information. Results confirm that postural hypo-reactivity to visual information is present in autism, but is contingent on both visual environment and development.

Keywords: Autism, Posture, Development, Sensorimotor, Virtual reality, Motion perception.

Introduction

Autism is a behaviorally variant phenotype with a neurogenetic basis characterized by atypical communication and social interaction, co-occurring with restricted interests and repetitive behaviours (American Psychological Association 1994). Visual information processing is also atypical in autism, defined by a *''perceptual signature''* characterized by superior performances on perceptual and cognitive tasks where local or detailed processing of spatial information is advantageous, and by a decreased ability or optional processing for complex types of information requiring either integrative, dynamic or global analysis (see Mottron and Burack 2001; Mottron et al. 2006); Dakin and Frith 2005; Behrmann et al. 2006; Bertone and Faubert 2006; Happe and Frith 2006; Simmons et al. 2009; Bertone et al. 2010; for reviews).

Posture is regulated via the integration of signals originating from three afferent sensory systems: the somatosensory, the vestibular and the visual systems (Peterka and Benolken 1995; Nolan et al. 2005). These signals are then used by the cortex and cerebellum to produce an appropriate motor output within a changing visual environment. A deficit in any of these systems can affect posture and balance. Given autism's *''perceptual signature''*, altered postural regulation is expected since visual information processing is involved in several visually-contingent behaviors, including maintaining posture, or balance. Although abnormalities of motor behavior, most often described as ''associated symptoms'', (i.e., either clumsiness, fine/gross motor deficits, apraxia, alterations in motor milestone development, etc.…) have been well documented in autism (Teitelbaum et al. 1998; Ghaziuddin and Butler 1998; Ming et al. 2007), relatively few studies have directly assessed either balance and/or postural reactivity in autism. In one such study, Gepner et al. (1995) reported an attenuation of reactivity to a radiating full-field optic flow stimulus, which typically induces the illusory perception of self motion, particularly for fast visual motion (see Gepner and Mestre 2002a). This study involved a small group of five young children with autism whose ages ranged between 4 and 7 years (and whose intellectual level of functioning was not documented). Gepner and colleagues concluded that persons with autism, especially those with low functioning autism (LFA), were insensitive to dynamic visual information with regards to posture compared to control participants, which probably originated from an impairment in motion perception; a lack of attention to stimuli was also suggested. However, it can also be argued that postural attenuation might have resulted from a motor functioning impairment in the autism group (particularly in the LFA group), resulting in inadequate motor output despite appropriate sensory functioning. These and other results related to the perception of both social and non-social information (Gepner and Mestre 2002a) have been used to propose that a ''rapid visual motion integration deficit'' (Gepner and Mestre 2002b), and more recently, a ''temporo-spatial processing disorder'' (Gepner and Féron 2009) may underlie postural anomalies in autism.

Subsequent studies assessing posture in autism have manipulated proprioceptive input by having participants stand on foam (or not) under different visual conditions. For example,

Molloy et al. (2003) demonstrated that on average, autistic children were less stable when standing passively and blindfolded, thus eliminating visual cues, whether or not proprioceptive information was modified. Reflecting over-reliance on visual input for maintaining balance in the autism/ASD group, this result was interpreted as evidence for a multi-modal dysfunction in the integration of information originating from visual, somatosensory, and vestibular afferences in autism. Using a larger sample of 79 high-functioning autistic participants aged between 5 and 52 years, Minshew et al. (2004) demonstrated that the postural stability of autistic participants was reduced when proprioceptive input was disrupted by a sway-referenced platform. In addition, results demonstrated that postural control started to develop later in the autism group (12 years of age compared to 5 years in the control group) and never reached neuro-typical, adult-like levels. These results were also interpreted as evidence for both delayed and underdeveloped postural control in autism, and also argued to result from a deficit of multimodal sensory integration between the different neural systems underlying postural control in autism.

Taken together, all of these results suggest atypical or underdeveloped postural control in autism that may derive from a multi-modal sensory integration deficit, either resulting from impaired complex motion perception (Gepner et al. 1995), or from atypical integrative functioning between any of the subsystems involved in postural control (Molloy et al. 2003; Minshew et al. 2004). In order to isolate the subsystems underlying postural control in autism, we have assessed postural behavior in response to immersive visual environments differing only as a function of oscillation frequency, while the other sub-systems, namely the somatosensory and vestibular systems, were kept constant. A fully immersive virtual reality approach was used to measure postural reactivity and stability in autism relative to a sway-inducing virtual tunnel (see ''Methods'' section) oscillating at three different frequencies (see Greffou et al. 2008; Piponnier et al. 2009). Postural behavior was assessed above and below the age of 16 years (participants included in either 12–15 years, or 16–33 years age groups) in order to assess whether postural behavior differs as a function of development. The age ranges used to create our groups were chosen based on previous findings demonstrating that postural reactivity to the exact same visual environment used in the present study reached adult-like

levels at 16 years of age for neurotypical participants (Greffou et al. 2008). In addition, the immersive nature of our virtual reality approach minimizes possible confounding variables such as inattentiveness to the visual environment (Gepner et al. 1995) for both autistic and control participants. This approach also allows for the manipulation of visual environment characteristics (tunnel oscillation frequency) on a continuum, rather than on a categorical level (present or absent).

Methods

Participants

The autistic and typically-developing (TD) participant groups were placed in either of two age groups: 12–15 year-olds and 16–33 year-olds. Therefore, the study included a total of four groups: a 12–15 year-old autism group ($n = 8$; M = 13.0 ± 1.3 year-old), a 12–15 year-old TD group ($n = 11$; M = 13.6 ± 1.6 year-old), a 16–33 year-old autism group ($n = 8$; M = 21.0 ± 5.9 year-old), and a 16–33 year-old TD group ($n = 23$; M = 23.0 ± 5.4 year-old).

Autism Group

Sixteen individuals (3F; 13 M) with autism were randomly extracted from Rivière-des-Prairies' hospital database and invited to participate in this study. Autism was diagnosed using the Autism Diagnosis Interview-Revised (Lord et al. 1994) and the Autism Diagnosis Observation Schedule (Lord et al. 2000), both of which were conducted by a trained clinician-researcher (LM) who obtained reliability on these instruments. Thirteen of the participants with autism scored above the ADI and ADOS cut-off in the three relevant areas for diagnosis (social, communication, restricted interest and repetitive behaviours). One autistic participant did not score above cut off in the Communication domain on both instruments; and two participants were administered an expert (but not standardized) clinical DSM-IV diagnosis of autism following a direct observation based on the ADOS procedure. Participants with other developmental DSM-IV Axis 1 diagnoses, except hyperactivity and language disorders, potentially relevant Axis 3 diagnoses, non-corrected-to-normal vision (20/20 Snellen acuity

for both eyes) and without adequate stereoscopic vision were excluded from enrolment in this study. Two autistic participants (one in each age group) were taking Concerta (a slow-release psychostimulant used to manage ADHD) at the time of testing as part of their daily routine. All participants in the autism group had full-scale Wechsler IQ scores in the normal range (12–15 year-olds: 98.75 ± 16.2; 16–33 year-olds; 101.13 ± 12.0).

<u>Typically Developing Group</u>

Performance of participants with autism was compared to that of thirty-four typically developing (TD) individuals. TD individuals were recruited by word of mouth in the community, and none of them reported problems when screened by a semi-structured interview documenting history of psychiatric or neurological condition, learning disabilities, family history (1°) of mood disorders, pervasive developmental disorders or schizophrenia, defective vision or audition and intake of medication. All participants were informed of the goals of the study and nature of the tasks and their consent was obtained. All participants were compensated monetarily for their time. Testing commenced after the ethics committees at the Rivière-des-Prairies Hospital and at the University of Montreal (where the testing took place) approved of the study.

Apparatus

Postural reactivity to visual information was assessed using a fully immersive virtual environment (CAVE system, FakespaceTM). The CAVE is an 8 x 8 x 8 feet room including three canvas walls (one frontal and two laterals) and an epoxy floor, all serving as surfaces for the projection of images (Fig. 1). The resolution of each surface image was 1,280 x 1,024 pixels, and was generated by Marquee Ultra 8500 projectors.
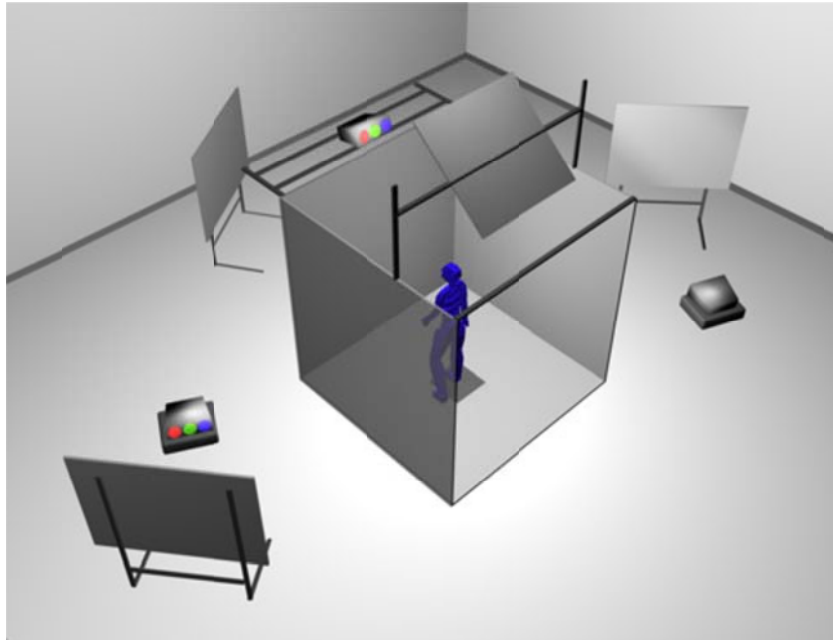
C3-Figure. 1 The CAVE is an 8 x 8 x 8 feet room that includes three
walls (one frontal and two lateral) and a floor that all serve as surfaces
for the projection of images

The CAVE was under the control of a SGI ONYX 3200 ® computer equipped with two Infinite Reality II graphics cards and a magnetic motion tracker system (Flock-of-Birds®) measuring postural reactivity by registering body movement at the head level. A previous study conducted in the laboratory (Faubert and Allard 2004) along with some pilot data using the same setup as was used in the present study showed that the measures taken at the head level (sensor positioned on the stereo goggles) yielded comparable results to those obtained when sensors were positioned on the lower back (lumbar 2–3). This demonstrates that, at least under our present conditions, the postural response of our participants resembled that of an inversed pendulum motion pattern. We have therefore decided to use only the sensor at the head level so as to avoid adding methodologically superfluous and potentially invasive lumbar sensors. The polarized stereoscopic goggles (Crystal Eyes®, StereoGraphics Corporation; Fig. 2) were equipped with a magnetic motion sensor allowing for the precise tracking and

measurement of their motion (thus, the motion of participants). Three dimensional vision being the result of the computation of two different images (one from each eye) by the brain, wearing of stereoscopic goggles allowed for the alternating occlusion of the left and right eyes at a high frequency (96 Hz). This occlusion was synchronized with the projection frequency on the screens, resulting in a three-dimensional perception of the environment. For more details on the equipment used, please visit the following website: http://vision.opto.umontreal.ca/English/Techno/CAVE.html.

C3-Figure. 2 The stereoscopic goggles

Procedure

Participants were first familiarized with the virtual environment. Visual acuity and stereoscopic vision were then assessed without glasses (using a Snellen eye-chart and a Random Dots Stereo-acuity Test). Participants were then asked to wear the stereoscopic goggles, and were positioned at 1.50 m from the CAVE's central wall with shoes off, feet together, and arms crossed. This position was chosen in order to minimize the use of individual strategies from the limbs to maintain posture, and helped maximize the effect of the visual stimulation (Kawakita et al. 2000). For all conditions, participants were asked to fixate

a red dot located at the horizon. Behavioral information was recorded as 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'' (Fig. 3; for a video of this paradigm: http://vision.opto.umontreal.ca/Techno/CAVE. html). The tunnel had an inner texture made of a checkerboard pattern, where each high-contrast square was scaled for linear perspective (for a detailed description, see Greffou et al. 2008; Piponnier et al. 2009). Two types of visual environments, *dynamic* and *static*, were used in this study.

For the dynamic condition, the simulated motion of the tunnel was defined by an anterior–posterior (front-back) sinusoidal translation motion oscillating around the participants at 3 different frequencies: 0.125, 0.25, or 0.5 Hz (for further details on the choice of these frequencies or on the physical properties of the tunnel, please refer to Greffou et al. 2008). For each frequency, participants performed three 68 s trials, resulting in a total of 9 *dynamic* trials, presented in a pseudo-random order. The initial frequency was randomly selected and each consecutive presentation of a given frequency was always separated by at least one presentation of each of the two other frequencies. *Static* conditions served as control conditions, thus allowing us to separate the effect of dynamic visual stimulation on postural reactivity from that of static visual stimulation and spontaneous sway. In the *static tunnel* condition, participants had to fixate a red dot presented at the horizon during two 68 s trials, while standing in the virtual tunnel in its static state (0 Hz, i.e. motionless). Since the structure, dimension and texture of the tunnel were identical in both *dynamic* and *static* conditions, the unique variable differentiating the two conditions was its apparent motion. For the *eyes closed* condition, participants were asked to position 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, whether dynamic or static, affected postural reactivity. In summary, all participants performed thirteen 68 s trials in the following order; 2 *static* tunnel trials, 9 *dynamic* tunnel trials, and 2 *eyes-closed* trials. A trial was considered incomplete if either a participant lost

balance during the trial (i.e., he or she could not remain standing with feet together), or asked for the trial to be stopped. If a participant was unable to complete two out of the three dynamic trials for a given oscillation frequency, his/her data was excluded from statistical analyses.
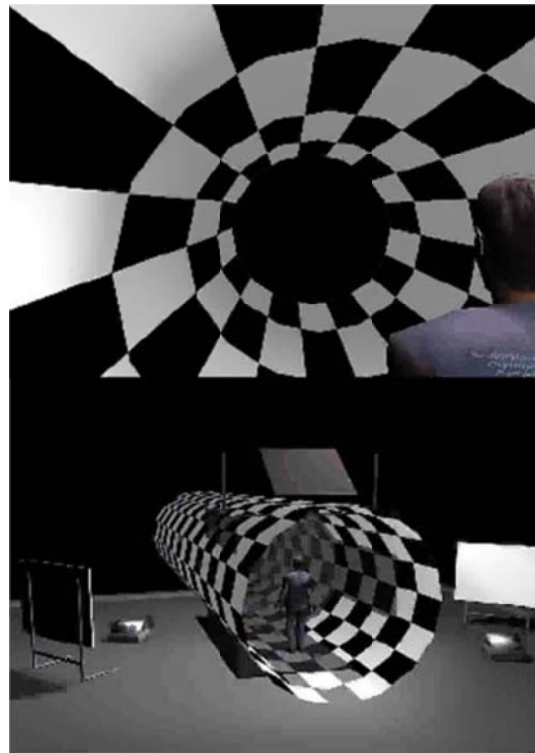
C3-Figure. 3 The virtual tunnel paradigm (http://vision.opto.umontreal.ca)

Behavioral Measures

Changes in posture were monitored using two measures: Body Sway (BS) and Postural Perturbations (PP), (see Greffou et al. 2008). BS is the anterior-posterior displacement of a participant as a function of the virtual tunnel's oscillation frequency. Due to the variation of height as a function of age group, angular displacement (Fig. 4) was used as the dependent measure of postural reactivity as opposed to linear displacement. PP is defined as the root mean squared (RMS) of total body velocity in the horizontal plane (i.e., anterior-posterior ''z axis'' and medial–lateral displacements ''x axis'') in angles per second (Faubert and Allard

2004; Greffou et al. 2008; Piponnier et al. 2009). This measure was used in order to quantify postural perturbations induced by the visual stimuli. The PP measure is distinct from the BS one in that it is not computed relative to a single specific frequency; rather, it reflects body instability at all frequencies minus the one at which the tunnel ''moves'' during the trial of interest.
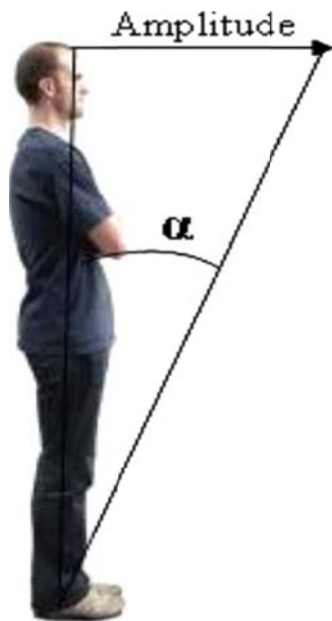
C3-Figure. 4 Angular displacement of a person

Results

Statistical Analyses

Separate analyses were performed for Body Sway (BS) and Postural Perturbations (PP) given that each of these two variables represents a different element of postural reactivity: BS reflecting synchronicity to stimulation, and PP reflecting general instability. In the dynamic tunnel condition, results from 3 trials were averaged for each frequency, resulting in one value per frequency for each participant. The same principle was applied for the control conditions: 2 trials per frequency were averaged for each participant; therefore, each participant had only one score per frequency, per condition (dynamic tunnel, eyes closed and static tunnel). Raw scores were converted to log values. Note that the data of one autistic participant in the 12–15 year-old group was removed from statistical analyses as he was unable to complete all of the 0.25 Hz trials due to dizziness and to technical problems during testing.

Body Sway Analyses (BS)

An Age (2) x Group (2) x Frequency (3) mixed factorial analysis of variance (ANOVA) was performed for the dynamic condition. A significant main effect of Age (F(1, 45) = 13.01, p = .001, $\eta2$ = .224) and a non-significant Group (autism vs. TD) x Frequency interaction (F[1.84, 82.90] = 0.52, p = .58) demonstrated that younger participants (12–15 year-old) swayed more than older participants across all frequencies regardless of whether they belonged to the autism or TD groups. Moreover, a 2 (Group) x 2 (Age) x 3 (Frequency) mixed factorial ANOVA revealed a significant three-way interaction F[1.84, 82.90] = 3.67, p = .033, $\eta2$ = .075); pairwise comparisons using Bonferroni correction revealed that amongst the autistic group, the 12–15 year-olds manifested significantly more Body Sway than did the adults for the 0.125 and 0.25 Hz. The same was true of the TD groups, where 12–15 year-olds showed significantly more body sway than did the adults but this time for the 0.25 and 0.50 Hz. A between-group difference in Body Sway for younger participants failed to reach statistical significance for all of the frequencies, but a trend was noted at 0.50 Hz where younger participants with autism swayed less than younger TD ones (See Fig. 5).
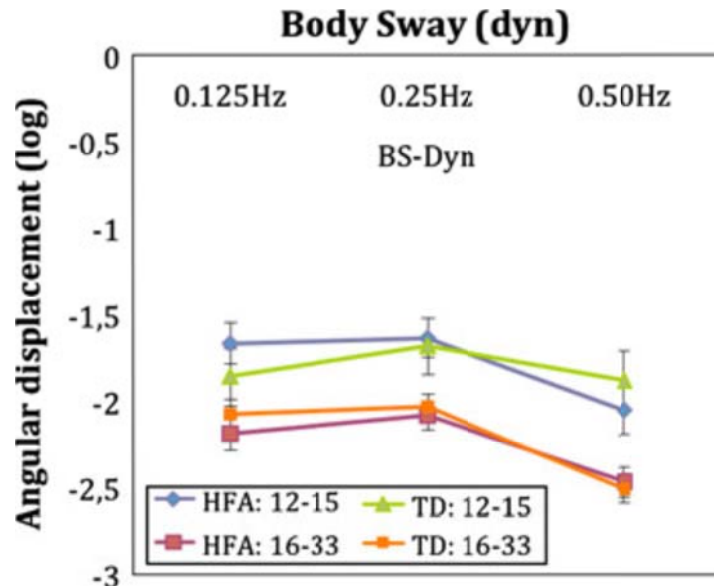
C3-Figure. 5 Body sway as a function of frequency and group

Age (2) x Group (2) x Frequency (3) mixed factorial analyses of variance were also performed for both of the Eyes Closed (EC) and Static Tunnel (ST) conditions (Figures not shown). For EC, no significant main effect of Group (F[1, 45] = 1.27, p = .27) nor a significant three-way interaction (F[2, 90] = 1.19, p = .31) were found. Likewise, for the Static Tunnel condition (ST), no significant main effect of Group (F[1, 45] = 0.072, p = .79) or a significant Age x Group x Frequency interaction were found (F[2, 90] = 1.31, p = .28). Finally, an ANOVA comparing Eyes Closed and Static Tunnel, where BS scores were collapsed across frequencies, showed that participants were less reactive during the Static Tunnel condition as compared to during the Eyes Closed condition (F[1, 6] = 7.02, p = .038) regardless of frequency, as no significant Condition x Frequency interaction was found (F[2, 12] = 3.31, p = 0.072).

Postural Perturbations Analyses (PP)

Age (2) x Group (2) x Frequency (3) mixed factorial analyses of variance were performed. For the dynamic condition, a significant main effect of Age ($F[1, 45] = 20.16$, $p = .000$, $\eta2 = .309$) demonstrated that younger participants (12–15 year-old) were less stable than older participants across all frequencies regardless of whether they belonged to the autism or TD groups. Furthermore, a 2 (group) x 2 (age) x 3 (Frequency) mixed factorial ANOVA revealed a significant three-way interaction ($F[1.67, 75.13] = 4.23$, $p = .024$, $\eta2 = .086$); pairwise comparisons using Bonferroni correction revealed that at 0.50 Hz, the 12–15 year-old autism group (M = -1.62, SD = .18) manifested significantly more postural stability than did the 12–15 year-old TD group (M = -1.42, SD = .32), ($t(16) = 2.08$, $p = .043$); as was previously mentioned, the same tendency was observed for BS although it failed to reach statistical significance for 0.50 Hz (See Fig. 6).

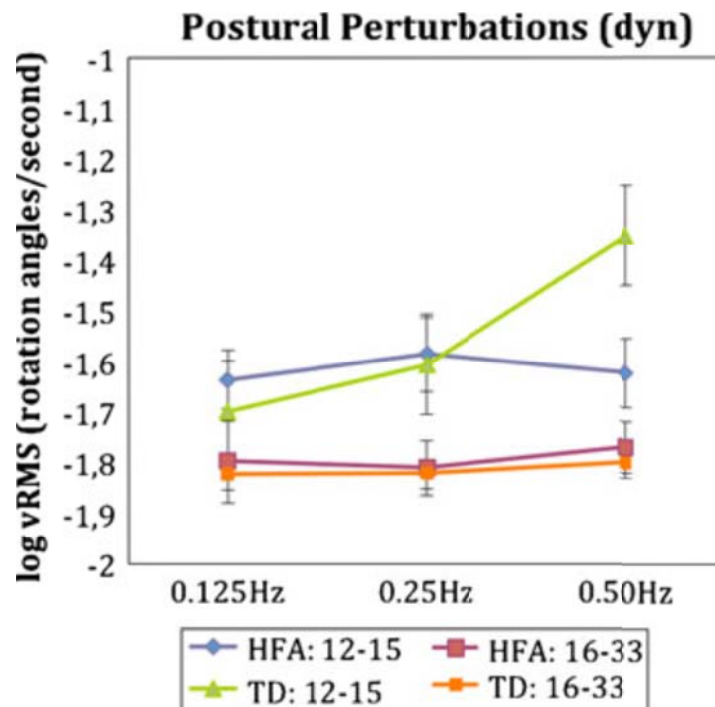C3-Figure. 6 Postural perturbations as a function of frequency and group

Age (2) x Group (2) x Frequency (3) mixed factorial analyses of variance were also performed for both the EC and ST conditions (Figures not shown). For EC, no significant main effects of Group was revealed (F[1, 45] = .029, p = .86) nor was a significant three-way interaction (F[1.07, 48.07] = .36, p = .57). Similarly, for ST no significant main effect of Group (F[1, 45] = 1.11, p = .30) or a significant Age x Group x Frequency interaction were evidenced (F[1.84, 82.56] = .44, p = .63). Finally, an ANOVA comparing Eyes Closed and Static Tunnel, where PP scores were collapsed across frequencies, showed that participants, as was the case for BS, were more stable during the Static Tunnel condition as compared to during the Eyes Closed condition (F[1, 6] = 5.10, p = .065) regardless of frequency, as no significant Condition x Frequency interaction was found (F[1.2, 7.2] = 2.80, p = 0.14).

Discussion

Although atypical motor behaviors are often described as associated behavioral symptoms of autism, their etiology remains unknown. Given the altered visually-related information processing in autism, an important component of motor regulation, we assessed the visual and vestibular components involved in postural reactivity in autism by measuring perturbation and body sway induced by a virtual tunnel oscillating at different frequencies for younger and older participants with autism. Compared to typically-developing participants, younger participants with autism were hypo-reactive showing significantly less postural perturbation to the sway-inducing virtual tunnel only at the highest oscillation frequency (0.50 Hz). No significant differences in postural reactivity were found between the two older groups across the three frequencies tested in the dynamic condition. In addition, postural behavior did not differ between groups when immersed in control environments, where afferent visual input was either present and static (immersed in static tunnel) or absent (eyes closed condition). These results suggest that hypo-reactivity to visual-inducing information in autism is contingent on both visual environment (ex: speed of visual stimuli) and development (chronological age), and probably not the result of a vestibular dysfunction; if such were the

case, between groups differences would be found throughout all of the experimental conditions, particularly Eyes Closed, where the vestibular system is more strongly solicited.

Atypical Postural Behavior And Dynamic Information Processing in Autism

As was mentioned in the Introduction, the paradigm used in the present study is novel in that postural behavior in autism was not simply assessed as a function of whether afferent visual input was present or not (i.e., eyes-closed vs. eyes-opened). We assessed the implication of vestibular and visual components of postural behavior by measuring how this behavior was differentially affected by manipulating the dynamicity (tunnel frequency oscillation) of the visual environment wherein the participants were immersed. Results demonstrated that for younger participants with autism (12–16 years), hypo-reactivity (i.e., less postural perturbation) to a sway-inducing visual environment was only manifested for the highest oscillation frequency (0.50 Hz); between-group differences were not demonstrated for slower oscillation frequencies. Moreover, a similar trend was noted for the Body Sway measure where young participants with autism swayed less than the young TD; body sway being mostly a measure of synchronicity to stimuli (see ''Methods'' section), this implies that our younger autistic participants seem not to have synchronized normally to the fastest stimulation frequency whereas they were able to do so for lower frequencies. In summary, autistic participants were able to integrate and translate most sensory information into an appropriate motor response under most experimental conditions except when the processing and integration of fast visual stimuli was required.

These results are consistent with the ''visual-motion integration deficit'' (Gepner and Mestre 2002a) and/or the ''temporo-spatial processing disorder'' (Gepner and Féron 2009) hypotheses proposing that atypical postural reactivity in autism is specific to fast moving visual stimulation. In general, these hypotheses are based on findings of decreased postural reactivity of autistic participants to a 2-dimensional flow-field, defined by an oscillating circularly-symmetric, frequency-modulated concentric grating (Gepner et al. 1995), particularly for fast visual motion (Gepner and Mestre 2002a). In these two studies (the latter described as a replication and extension of the former), the oscillation frequency—or *driving*

frequency—of the grating was set at 0.2 Hz, resulting in different local angular velocities across the stimuli since the spatial frequency of the concentric rings defining the flow field decreased from center of focus of expansion/contraction. It is important to note that the effect of velocity on reactivity was computed by transforming (Fast Fourier Transformation or FFT) center-of-pressure measures into the fore-aft sway axis into components at each local angular velocity (ranging from 6° to 100°/s). Therefore, the interpretations of Gepner and colleagues are based on postural reactivity findings with respect to local (peak) angular velocities, and not to the consequence of manipulating the overall velocity of the sway-inducing flow-fields. It is also worth noting that although the hypotheses advanced by Gepner and Mestre were based on results originating from rather small sample sizes (i.e., Gepner and Mestre 2002a: autistic disorder, $n = 3$; Asperger $n = 3$; neurotypical, $n = 9$), they are consistent with ours as only young participants with an autistic disorder diagnosis (and not Asperger) demonstrated differential reactivity to visual information.

In the present study, three different dynamic driving frequencies were assessed (0.125, 0.25 and 0.5 Hz). By assessing postural behavior under different levels of dynamic visual stimulation, and not only comparing postural behavior in dynamic versus static environments, perceptual versus visuo-motor origins of atypical postural reactivity in our autism group were dissociated. The finding that postural behavior in the autism group was comparable to that of controls for the lower velocities argues against the suggestion that atypical postural behavior in autism is due to motion perception impairments (Gepner et al. 1995). Specifically, a motion perception deficit would predict atypical reactivity across all oscillation frequencies assessed, since the visual environment induced frequency-dependant sway for most conditions in the autism group. This finding is especially pertinent since the frequency-contingent autistic behavior occurred within an identical dynamic visual environment in all frequency conditions (except for its velocity level), and cannot be explained by inattention to stimuli, given the immersive character of the virtual visual environment and the small intra-subject variance between the 3 trials at each frequency. In addition, although there is some evidence of *motion perception* impairments in autism under specific experimental conditions (Bertone et al. 2003; see Bertone and Faubert 2006; Kaiser and Shiffrar 2009 for reviews), it is unlikely that such

subtle perceptual deficits alone would translate into the atypical postural behavior observed in this study, given the intensity of the high-contrast information defining the virtual tunnel.

Plausible neural mechanisms contingent on dynamic information processing include the visuo-cerebellar circuits due to their role in the speed and temporal coding of dynamic visual input. Interestingly, visuo-postural miscoupling is representative of a sensory-motor coupling disorder, first described 40 years ago (Ornitz and Ritvo 1968; Ornitz 1974) as a possible etiology of some autistic behaviors (see Ornitz et al. 1985: visuo-vestibular disconnect). In addition, anomalies of cerebello-premotor-motor cortex loops, due to the contribution of both the cerebellum and the basal ganglia to real-time fine-tuning of motor output and to motor learning via their projections to the motor, premotor, prefrontal, temporal and parietal cortices may also be candidate mechanisms that are underdeveloped in autism. This disordered under- or over- visuo-postural coupling in children with ASD may partly explain sensory-motor and motor disturbances, such as poor motor coordination, poor or enhanced postural control, and gross or fine motor clumsiness (Ornitz 1974; Damasio and Maurer 1978; Kohen-Raz et al. 1992; Leary and Hill 1996; Green et al. 2009 for reviews).

Developmental Trend of Postural Behavior in Autistic and Neurotypical Individuals

Previous results assessing visually-driven postural reactivity during typical development demonstrated that both children and young adolescents show less stability in reaction to dynamic visual scenes (dynamic virtual tunnel, as was used in this study) than adults; they reach adult-like levels between 16 and 19 years of age, suggesting an important transitory period for sensorimotor development (Greffou et al. 2008). In the present study, autistic and non-autistic participants who were 12–15 years of age exhibited more body sway and postural perturbations (vRMS) than did older participants. This finding is in accordance with the developmental trajectory observed in the aforementioned study. In addition, only in this younger age range were between-group differences contingent on the visual environment (oscillation frequency) manifested, suggesting that atypical postural reactivity behavior in autism is most evident before the critical period of sensorimontor development in neurotypical

individuals. In another study, Minshew et al. (2004) demonstrated that the postural control of persons with autism aged 5–52 year-old did not begin to improve until the age of 12 years, but never reached adult-like levels. Methodological differences (stimulation and measures) between the Minshew et al. (2004) and the present study may account for discrepancies regarding the transitory periods of sensorimotor development in autism. However, both studies suggest that development is an important component of atypical postural behavior in autism. These findings may be related to the reduced prevalence of motor deficits (fine motor control and programming) in older children with autism spectrum disorder, whether through natural progression, results of interventional therapy, or the combination of the two (Ming et al. 2007). In conclusion, the finding that postural hyporeactivity in autism occurred in the younger autism group when the inducing motion was fastest is suggestive of a delayed development of sensory-motor coupling in autism.

Vestibular and Somatosensory Effects on Postural Behavior in Autism

Although direct assessments of vestibular functioning in autism has been relatively limited, studies assessing vestibulo-ocular responses have demonstrated that vestibulo-related autistic dysfunction is most probably due to integrative deficits between the vestibular and other afferent systems (i.e., visual and/or somatosensory), rather than specific deficits to the peripheral vestibular system (Ornitz et al. 1985). This notion is consistent with our findings since a between-group difference in postural behavior (either reactivity or stability) was not evidenced for static conditions. In addition, behavior did not differ across the *different* static conditions (i.e., static tunnel vs. eyes-closed), suggesting that stability was typical in participants with autism whether or not afferent visual information was available. These results suggest that atypical postural reactivity for our autistic participants did not originate *uniquely* from a vestibular dysfunction. In addition, the lack of between-group differences for the static conditions (and most dynamic conditions) also suggests that if muscular or morphological differences between autistic and non-autistic participants were present (Leary and Hill 1996; Hallett et al. 1993; Vilensky et al. 1981), they were not significant enough to affect postural behavior under the experimental conditions and paradigm used.

Somatosensory afferent input was kept constant across conditions in this study given that the main goal was to isolate and assess the effect of visual environment on postural behavior (participants stood passively with their shoes off and feet together on a cushionless platform). In a previous study, modifying somatosensory input using a cushioned platform failed to significantly affect postural stability, defined by a sway area covered during a 30 s trial, in a group of 8 boys with ASD (Molloy et al. 2003). Results from this study also demonstrated that the stability of the ASD group significantly decreased during 'eyesclosed' conditions, regardless of whether somatosensory input was modified or not. This result was interpreted as suggestive of an over-reliance on visual input to maintain balance in the group assessed and is, in general, consistent with a reduced integration between different afferent sensory systems (Molloy et al. 2003; Minshew et al. 2004).

Findings in Relation to the Autistic Behavioral Phenotype

Although the presence of repetitive behaviors is considered to be a core characteristic of autistic spectrum disorder, there is presently little understanding regarding basic issues such as pathogenesis, purpose, preservation, and ultimately, the management of such behaviors in autism. Nevertheless, hypotheses implicating emotional (Baron-Cohen et al. 2000), executive (Ozonoff et al. 1991; Joseph and Tager-Flusberg 2004; Hill 2004; see Turner 1999 for reviews) and sensory/perceptual (Rimland 1994; O'Gorman 1967; Delacato 1974; Mottron et al. 2007) origins have been advanced. The latter hypothesis suggests that characteristic repetitive behaviors serve as coping mechanisms by persons with autism in response to an atypically interpreted environment. The present study demonstrated that the postural behavior (passive) of autistic participants differed under specific conditions of visual stimulation (i.e., higher oscillation frequencies), suggesting an association between perceptual environment and subsequent behavior. This association can be translated into real-life situations where temporally-changing visual environments are actively produced by behaviors often manifested by persons with autism that include: (a) visual rotation induced by repetitive spinning movements, and (b) the periodic visual stimulation induced by periodic hand or finger movements in the visual field. Whereas spinning behaviours are a reliable part of the autistic

phenotype (Bracha et al. 1995), atypical lateral fixations are associated with produced or searched periodic movements (Mottron et al. 2007).

The production of periodic body movements by autistics has generally been interpreted as the semi voluntary behaviour implicating a vestibular input within a framework of atypical sensory modulation (Ornitz 1974). However, our findings suggest that any explanatory model for atypical body movements in autism should consider a possible decoupling between vestibular and visual systems under certain conditions of dynamic visual stimulation. Anecdotally, this suggestion is supported by the frequently reported behavioural observation that prolonged rocking, spinning and whirling behaviours in autism do not result in dizziness (Ornitz 1974; Grandin 1996).

Limitations and Future Directions

Findings from this study are specific to participants diagnosed with autism who have an IQ comparable to that of typically-developing persons. It is unknown whether this pattern of results transfers across the autism spectrum (Asperger syndrome or Pervasive Developmental Disorder not Otherwise Specified). However, the passive nature of the fully immersive task makes it possible to assess children with limited language and cognitive ability. Future studies could compare different types of dynamic stimuli (e.g. swaying floors), and use non-periodic or unpredictable visual scene movement in order to verify whether abnormalities are manifested in other contexts where efficient visuo-motor integration and complex visual perception is required.

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their time and support. These results have been presented by Selma Greffou under the form of a poster at the 7th Annual Meeting for Autism Research in the year of 2008, London, UK; they have also been presented by Armando Bertone under the form of an oral presentation at the 30th European Conference on Visual Perception, Arezzo, Italy.

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PART B: Chapter 4-Study 4 (short communication)

Prolonged alterations of visually-driven balance control in children following a mild traumatic brain injury: a virtual reality study

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Abstract

Traumatic brain injury (TBI) is a leading cause of disability in children (Katz-Leurer, Rotem, Keren, & Meyer, 2009). Information about the way that a mild TBI affects balance in children is scarce (Gagnon, Swaine, Friedman, & Forget, 2004a), notably that concerning the visual contribution to these difficulties and their post-injury evolution across time. This study assessed the visual and vestibular components involved in postural control of children (9-18 years-old) having sustained a mTBI as a function of symptomatology and time post-injury. Postural reactivity (Postural Perturbations-PP and Body Sway-BS) was measured for Moderately-Symptomatic mTBI (MS-mTBI; n = 18), Low-Symptomatic mTBI (LS-mTBI; n = 19) and Control (n = 36) groups in response to a virtual tunnel oscillating at 3 different frequencies (Greffou, Bertone, Hanssens, & Faubert, 2008) at 3 distinct time intervals: 2 weeks (N = 73), 12 weeks (N = 67), and 12 months post-injury (N = 48; preliminary data). Results showed that at 2 weeks post-injury, the MS-mTBI group exhibited significantly more PP than the Control group when the tunnel was static and showed the same tendency when it was dynamic, though statistical significance was not reached. Conversely, at 12 weeks post-injury, the MS-mTBI group showed significantly more PP than the Control group under most of the dynamic tunnel stimulation conditions, but not when the tunnel was static; interestingly, only 11% of the participants in the MS-mTBI group were still moderately symptomatic at that time. Preliminary data suggests that the increased visually-induced postural instability observed in the MS-mTBI group at 2 and 12 weeks post-injury is no longer observed 12 months post-injury. No significant differences were found between groups for the BS measure. Taken together, these results suggest that children, having sustained mTBI and who are initially moderately symptomatic, generally show increased postural instability when exposed to optic flow stimuli, particularly 12 weeks post-injury, even when an elevated total score of symptoms is no longer self-reported; this instability appears to resorb within 12 months post-injury. This indicates that the balance difficulties reported following mTBI may be, at least partly, related to altered processing of dynamic visual information and do not appear to be solely predicted by the magnitude of the total score on a post-concussion symptoms scale (PCS-R; Lovell & Collins, 1998).

Introduction

Traumatic brain injury (TBI) is a leading cause of disability in children (Katz-Leurer, Rotem, Keren, & Meyer, 2009). Mild traumatic brain injuries (mTBI) represent over 85% of the 1.5 million traumatic brain injuries occurring annually in the US and the reported annual incidence of mild TBI in the child population (aged 5-14) in 1998-2000 was 733.3 per 100 000 (Bazarian et al., 2005). Despite normal structural neuroradiological results in mTBI, several physical, cognitive and emotional post-concussion symptoms are frequently reported in the first 3 months post-injury (Mittenberg, Wittner, & Miller, 1997).

Amongst the many physical symptoms that can arise following a TBI, balance problems have been commonly reported in adults (Cavanaugh et al., 2006); however, studies on balance difficulties following a TBI in children are scarcer, notably for the mild category thereof. Some studies have shown deficits in balance ability in children following a mTBI (Gagnon, Forget, Sullivan, & Friedman, 1998; Gagnon et al., 2004a; Guskiewicz, Perrin, & Gansneder, 1996). Moreover, the relative weight of vision in posture following a mTBI has not been thoroughly investigated. In a study performed on adults, it was suggested that sustaining mTBI induces an over-reliance on visual input when regulating posture in adults a few days post-injury (Rubin, Woolley, Dailey, & Goebel, 1995). Another study has shown that college athletes with mTBI failed to appropriately use visual cues to regulate their posture when assessed using the Sensory Organization Test (SOT) (Guskiewicz, Riemann, Perrin, & Nashner, 1997). Additionally, Slobounov et al., (2006) used a virtual reality environment to investigate postural responses to visual field motion in college athletes having sustained mTBI; they documented balance deficits induced by visual field motion 30 days post-injury, which was interpreted as a residual sensory integration dysfunction in concussed individuals. To our knowledge, no previous study has investigated the weight of visual input in postural

control alterations following mTBI in children, while concurrently evaluating the evolution of these characteristics up to one year post-injury.

Methods

Participants

Thirty-seven children, having sustained a mild traumatic brain injury (mTBI), whom were premorbidly typically developing, and whose ages ranged between 9 and 18 years old were recruited from the Montreal Children's Hospital trauma unit. They were then divided into two groups according to their symptomatology using the Post-Concussion Scale-Revised or PCS-R (Lovell & Collins, 1998): whenever a participant recorded a total score of ≥ 20, either at the moment of recruitment at the hospital or at our first testing session, he/she was included in the Moderately Symptomatic mTBI group (*MS-mTBI*); participants having a total score of $<$ 20 were included in the Low-Symptomatic mTBI group (*LS-mTBI*). Each mTBI participant was matched with a healthy child for age, gender, and premorbid level of physical activity. The *Control* group comprised 36 participants (note that the 37th control participant was excluded from the study as he has been diagnosed with a neurological condition after having completed our study).

Experimental Paradigm and Procedure

In order to track the evolution of potential postural control alterations following mTBI, participants underwent 3 testing sessions: 2 weeks post-injury (*Time 1*), 12 weeks post-injury (*Time 2*), and 12 months post-injury (*Time 3*). Prior to each testing session, participants had a complete eye examination performed by a qualified optometrist, had their post-concussive symptoms assessed by a self-report form PCS-R; they then underwent postural testing using the *Virtual Tunnel Paradigm* (see Greffou et al., 2008; Greffou et al., 2011). In the *Dynamic Conditions* the virtual tunnel moved at 3 different translation frequencies in the antero-posterior direction (0.125 Hz, 0.25Hz, 0.50Hz) and in the control conditions, either the tunnel

remained stationary (*Static Tunnel* condition), or the tunnel was not employed and participants instead closed their eyes (*Eyes Closed*; therefore isolating the contribution of visual input). Each trial lasted 68 seconds. In order to shorten testing time and the fatigability effects in our mTBI participants, the procedures were shortened relative to our previous studies, i.e., participants were presented with only one trial per frequency; hence, a total of four 68-seconds trials were presented for each one of the 0 Hz (static tunnel), 0.125 Hz, 0.25 Hz and 0.50 Hz stimulation frequencies. All trials were randomly presented and the final trial for all participants consisted of one 68 second trial with their eyes closed.

The behavioral measures employed were the same as in the Greffou et al., (2011) study. Again, postural reactivity were measured using Body Sway (BS), defined as the average anterior–posterior displacement, given in minutes of angles, of a participant at a given translation frequency during a complete trial as well as Postural Perturbations (PP), defined as the root mean squared of the total body velocity (vRMS) in minutes of angles per second, in order to quantify perturbations induced by the dynamic visual stimuli or due to spontaneous movements during both of the *Static Tunnel* and the *Eyes Closed* conditions.

Preliminary Results

Given the previously demonstrated effect of age on visually-induced postural behavior (Greffou et al., 2011; Greffou et al., 2008), analyses of covariance (ANCOVA) were performed with the factor Age being the covariate. Here, only significant results are presented.

Time 1

As can be seen in Figure 1, for the *Static Tunnel* condition, an ANCOVA revealed an almost significant main effect of GROUP ($F[2, 69] = 3.041$, $p = 0.054$). Indeed, the *MS-mTBI* group showed greater vRMS compared to the *Control* group ($p = 0.051$). Moreover, although

it did not reach statistical significance (probably because homogeneity of covariance was not reached), the ANCOVA for the Dynamic conditions revealed a tendency for the *LS-mTBI* group to have greater PP than the control group and the *MS-mTBI* group a still greater PP than the control group (F[2, 69] = 1.791, p = 0.174). This tendency was much stronger at *Time 2*.
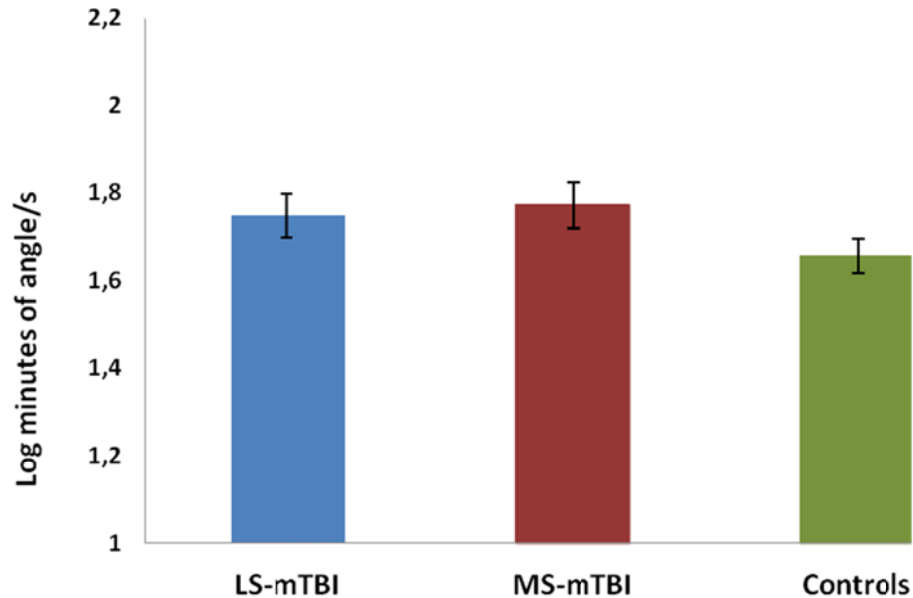
Figure 1. Postural Perturbations in Log vRMS (minutes of angle/s) during the *Static Tunnel* condition at *Time 1*. *SEM* bars are shown for each age group.

Time 2

As is represented in Figure 2, an ANCOVA performed on the PP measure during the *Dynamic Conditions* revealed a significant main effect of <u>GROUP</u> (*F*[2, 63] = 4.447, *p* = 0.016). More specifically, pairwise comparisons using LSD corrections showed the *MS-mTBI* group to have greater PP than the *Control* group (*p* = 0. 001) and than the *LS-mTBI* (*p* = 0.017) at the 0.125 Hz stimulation frequency. Likewise, the *MS-mTBI* group exhibited significantly more PP than the *Control* group when the tunnel oscillated at 0.25 Hz (*p* = 0.020).

Interestingly, at *Time 2*, only 11% of the participants in the *MS-mTBI* group remained moderately symptomatic, i.e., had a total score ≥ 20 on the PCS-R.
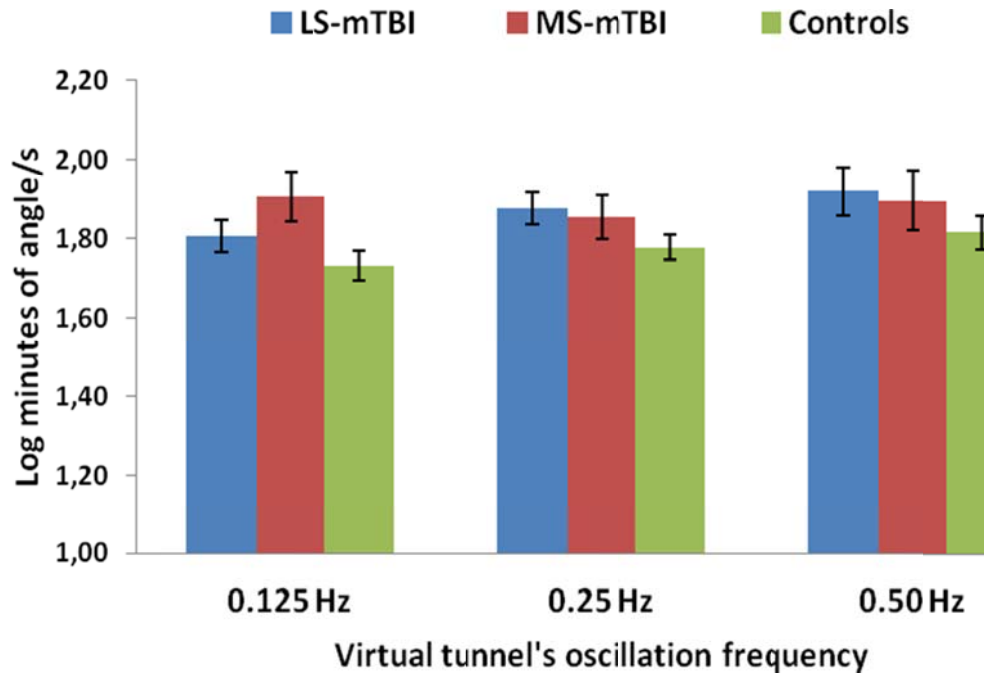
Figure 2. Postural Perturbations in Log minutes of angle/s as a function of oscillation frequency at *Time 2*. *SEM* bars are shown for each group.

Time 3 (preliminary results)

The main effect of Group on the ANCOVA for the PP measure on the *Static Tunnel*, which was significant at *Time 1*, was no longer significant at *Time 3* ($F[2, 46] = 0.459$, $p = 0.635$), neither was the main effect of Group on the ANCOVA for the PP of the Dynamic Conditions ($F[2, 44] = 0.547$, $p = 0.582$), which was significant at *Time 2*.

Discussion

In the present study, increased visually-induced instability was found for moderately-symptomatic mTBI children relative to their matched controls at 2 weeks post-injury (although not statistically significant) and 12 weeks post-injury when exposed to dynamic visual information. This is in accordance with previous findings where children with mild TBI continued to show balance deficits 12 weeks post-injury (Gagnon et al., 2004a) and that of Slobounov et al., (2006) where college athletes with mTBI demonstrated increased visually-induced postural instability in response to a visual field motion up to 30 days post-injury. Our findings may be explained by deficits in visual processing ensuing mTBI: a previous study by our group evidenced prolonged visual processing deficits for complex motion stimuli in children up to 12 weeks post mTBI (Brosseau-Lachaine, Gagnon, Forget, & Faubert, 2008). Furthermore, visuo-motor difficulties may also account for the visually-induced postural instability that we found in the *MS-mTBI* group at 12 weeks post-injury: interestingly, visuo-motor response time anomalies were found in certain children with mTBI when assessed with simple tasks involving moving visual stimuli or with tasks involving balance and more complex information processing up to 12 weeks post-injury (Gagnon, Swaine, Friedman, & Forget, 2004b). Finally, another important finding consisted in the fact that at 12 weeks post-injury, the time where the greatest postural instability was observed in the *MS-mTBI* participants, self-reported symptoms in this group had abated considerably when compared to that at 2 weeks post-injury. This finding could have implications with regards to the clinical management of pediatric patients following mTBI, especially in the light of the fact that symptoms resolution is generally seen as the green light for return to play (McCrory et al., 2005) and to other activities. Furthermore, these results could set the path for the development of sensitive and specific markers of dysfunction in these populations.

Acknowledgements

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Chapter 5: General Discussion

Visually-Driven Postural Control in Typical Development

The first study aimed at investigating the visually-driven postural regulation as a function of age (5 to 25 years of age) in young healthy individual, and as a function of velocity of optic flow stimulation. Akin to what was hypothesized, higher amounts of postural reactivity (for both BS and PP) were found in children compared to the young adults. Indeed, we demonstrated that for young children (5-7 year-olds), an important over-reliance on visual input was present as evidenced by the fact that most of the children in this group could not complete the trials. Regarding other age groups, postural reactivity to different frequencies of optic flow stimuli decreased significantly with age up until 16–19 years for both of the BS and PP measures. These results were interpreted as suggesting an important transition period regarding the maturation of the systems underlying sensorimotor integration at around 16 years of age. Findings of this study are further corroborated by the fact that, in our mTBI study (*Chapter 4*), increasing age was accompanied by a significant decrease in postural reactivity thorough all of the dynamic conditions and time sessions, however this time with a greater sample size ($N = 73$ at Time1; $N = 67$ at Time 2; $N = 48$ at Time 3). Indeed, ANCOVAs performed on the PP measure showed a significant main effect of *Age* for the dynamic conditions at Time 1 ($F[1, 69] = 26.941$, $p = 0.000$), Time 2 ($F[1, 63] = 36.785$, $p = 0.000$), and Time 3 ($F[1, 44] = 10.723$, $p = 0.002$). Likewise, ANCOVAs performed on the BS measure showed a significant main effect of *Age* for the dynamic conditions at Time 1 ($F[1, 69] = 24.083$, $p = 0.000$), Time 2 ($F[1, 63] = 22.787$, $p = 0.000$), and Time 3 ($F[1, 44] = 6.603$, $p = 0.014$). Additionally, in that same study, children having sustained a mTBI after 16 years of age and who were initially considerably symptomatic seemed to experience more postural instability when exposed to dynamic visual stimuli. Furthermore, results from our second study (*Chapter 2*) also indicate that important sensorimotor changes take place at about 16 years of age, since inter-group differences between autistic and control participants were only objectified before 16 years of age and were not observed after that age, i.e., in the 16-33 year-olds.

Interestingly, 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. It can be argued that 0.25 Hz could be a more natural speed of environmental movement, which makes it a frequency of choice for inducing sway (Dijkstra, Schnöer, Giese, & Gielen, 1994; Giese, Dijkstra, Schnöer, & Gielen, 1996; Schnöer, 1991). This is consistent with the findings of the other studies in this thesis where the 0.25Hz was the least efficient frequency in distinguishing groups from each other: in the autism study, inter-group differences were only observed at 0.50 Hz but not at 0.25Hz nor at 0.125Hz; furthermore, in the healthy aging study, BS was more elevated than that of the young adult group at 0.125Hz and 0.50Hz but not at 0.25Hz. Also, 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. 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 could have explained why 0.5-Hz sway was greater than 0.125-Hz sway in the younger children but not in the older groups (16 years and up). However, this is unlikely to be the case as in our second study on healthy aging, older adults exhibited more postural reactivity than younger ones regardless of body weight.

Similar to the BS findings, results from the present study clearly demonstrate a significant decrease in vRMS (or increase in stability) with age. More precisely, 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).

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.

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). (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 our 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.

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. However, this theory does not hold for older adults in our second study as decades of extra habituation to the surrounding visual world does not suffice to prevent postural instability.

Among the different developmental theories on postural control lies Woollacott and Shumway-Cook's (1990) who have argued in favor of two different explanations. The first one being 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. It is possible that the higher nervous system centers necessary to feedback postural control reaches maturity between 16-19 years of age and is delayed before that age range in autistic participants; indeed, younger autistic participants showed postural hypo-reactivity only before 16 years of age. Second, the "Systems Theory" claims that the development of independent stance emerges from the interaction among multiple neural and biomechanical components which are: 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 developmental 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. Given the multitude of elements that need to mature to become adult-like, it could be that youngsters with autism show a delay in the development of these subsystems but "catch up" with the neurotypical individuals at later ages. Likewise, it is possible that one or many of these systems is affected in children following mTBI but eventually recovers within one year post-injury.

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: the ankle strategy in which balance adjustments are made at the ankle joint, the hip strategy where adjustments are made at the hip, and 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. 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.

Visually-Driven Postural Control in Healthy Aging

Desiring to elaborate on our first study on visually-driven postural reactivity in children (Greffou et al., 2008), our second study aimed at investigating visually-driven postural regulation as a function of age and optic flow velocity in young, middle-aged and

older healthy adults (25 to 85 years of age). As was hypothesized, the high amounts of postural reactivity and the over-reliance on visual input present in children and adolescents returned later on in life. Indeed, the most important finding of this study was that postural reactivity to optic flow stimuli increased linearly with age, regardless of optic flow velocity. Results showed that both BS and PP augmented linearly with age for all of the temporal frequency conditions except one (BS at 0.25 Hz was stable as a function of age). This could not be explained by differences in spontaneous sway induced by non-visual sensory feedback systems (i.e., estibular, proprioceptive, and cutaneous). Thus, the fact that over-reliance on visual information that was observed in children and adolescents (Greffou et al., 2008) returns later in life, implies that significant sensorimotor changes occur not only around 16 years of age, but also again after 60 years of age.

Although the behavioral outcome (visual-dependence) is similar in typically developing children and healthy aging individuals, the etiology of the sensorimotor changes underlying this behavior is probably different. The "Systems Theory" mentioned earlier for the development of posture in humans proposed by Wollacott and Shumway-Cook (1990) claims that the development of independent stance emerges from the interaction among multiple neural and biomechanical components (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) and that transitory phases of development occur whenever one or more of the components mature. Hence, it is conceivable that, at least in typical development, all of these components may reach maturation around 16 to 19 years of age, and that some of them start becoming less efficient commencing at about 45 years of age and significantly less so at 60 years of age. It can also be argued that it is the ability of the nervous system to perform complex processing of stimuli that varies as a function of age (Faubert, 2002), developmental type, and brain injury; this idea shall be further discussed in the upcoming sections.

Given fully immersive, passive (small cognitive load), and highly contrasted nature of our stimuli, it is unlikely that the differences between the elderly and the young groups were driven by changes in attention allocation like was suggested by some (Mahboobin, Loughlin, & Redfern, 2006). Moreover, the finding that both of the middle-aged and the elderly groups showed greater PP than the young group in the Static Tunnel condition could be explained by age-related changes (decrements) of the following nature: neuromuscular (Woollacott et al., 1988), vestibular (Furman, & Cass, 2003), and somatosensory (Qiu et al., 2012). Although these kinds of changes may be sufficient to explain age-differences in passive quiet standing (either with eyes closed or eyes open), they are not sufficient to explain the age-differences observed when the tunnel was dynamic. Indeed, the ANCOVA revealed that the differences between the elderly group and the young group on the PP measure was still present after controlling for spontaneous sway in the absence of dynamic visual stimulation (Static Tunnel), regardless of stimulation frequency. One could think that this could be explained by the fact that visual perception changes in the elderly (i.e., stimuli are misperceived or magnified), however, this is unlikely to be the case for the following reason: on the BS measure, the older adults exhibited more sway at the very frequencies of the stimulation, thereby showing increased synchronized postural responses to each of the stimulation frequencies. In other words, it is the magnitude of the already-existing postural response (in the young ones) that appears to have increased with age.

It is probable that the increase in the magnitude of postural response is contingent on stimulus complexity: a review on the visual deficits related to aging by Faubert (2002) has argued that age-related changes in visual perception seems to rather be a consequence of stimuli complexity (computational load or complexity of neural network) than a consequence of the impairment of specific visual systems. Linking this idea to our findings, in the Static Tunnel condition, the stimulus is mainly luminance and depth defined, whereas in the Dynamic Tunnel conditions, an extra degree of complexity is added by introducing the *motion* variable. The fact that the complexity of the stimuli to be processed and integrated by the central nervous system augmented in the dynamic compared to the static conditions may have

more importantly challenged the postural control system of the older participants, thereby creating a saturation of this system and, consequently, the emergence of sub-optimal patterns of motor output (greater PP and BS). This explanation could also explain why in the autism and in the mTBI studies, postural reactivity was altered: alterations of the CNS, albeit of an innate or acquired nature, are likely to make the postural system more fragile, thereby causing it to saturate more easily.

In the same line of ideas, although some sensory systems may individually undergo age-related losses (e.g., vestibular system), multi-sensory integration has often been shown to become less efficient with age (for a review, see Mozolic, Hugenschmidt, Peiffer, & Laurienti, 2012). As was mentioned in the introduction, three sensory systems are utilized for postural regulation: the vestibular, the somatosensory, and the visual one; the complex integration of the afferents from each of these sensory modalities within the central nervous system is then required and appropriate motor commands and efferents have to be generated accordingly. It can be hypothesized from our findings that starting from 45 years of age, the over-reliance on vision observed in children returns and even more so after age 60. This could be due to the fact that the visual system is a more blue-printed and predominant system than the other ones, making it the default system in the face of sensorimotor difficulties; this is supported by the fact that the vestibular system has recently been shown to not be of capital importance for upright stance control (Bringoux et al., 2007). This argument is also consistent with our previous findings where visual input was disproportionately influential compared to non-visual sensory inputs on postural regulation in younger healthy children until reaching adult-like levels around 16-19 years of age (Greffou et al., 2008).

The prevalence of falls in the elderly is elevated and highly costly to society (Rubenstein, 2006; Stevens, Corso, Finkelstein, & Miller, 2006). The finding that over-reliance on vision returns in advanced age is important in that it could have valuable implications for the prevention of falls in the elderly. For example, it could be used to develop better management of living commodities, or more adapted physical training programs.

Following the same line of thoughts, falls are often accompanied by medical complications, such as TBI; thus, since both advanced age and a history of mTBI have been shown to affect visually-dependent postural control, it would be interesting to investigate this component in a population defined by both of these characteristics. In the future, it would also be interesting to study how previous experience/expertise in dealing with fast moving visual scenes (e.g., experienced drivers or ex-athletes) influences visually-driven postural regulation in aging individuals and/or patients with mTBI.

Visually-Driven Postural Control in Atypical Development (Autism)

The objective of the third study was to explore how diffuse alterations to the CNS, of an innate nature, exemplified here by persons with autism, influences visually-driven postural control as a function of dynamic visual stimulation velocity in a group of young individuals with high-functioning autism. As was expected, children with autism showed altered postural regulation as manifested by hypo-reactivity to visual information, but was contingent upon both visual environment and chronological age. Indeed, at the highest oscillation frequency, younger autistic participants (12–15 years) showed significantly less instability compared to younger typically developing participants; this difference was not evidenced for older participants (16–33 years). No such significant differences in postural behavior were found between the 4 groups in the absence of dynamic visual information. This suggests that atypical postural reactivity behavior in autism is most evident before the critical period of sensorimotor development in neurotypical individuals and is only manifested when faced with optic flow stimulation of certain velocities (i.e., 0.50 Hz, a complex and fast visual stimuli). No significant differences in postural reactivity were found between the two older groups across the three frequencies tested in the dynamic condition. In addition, postural behavior did not differ between groups when immersed in control environments, where afferent visual input was either present and static (immersed in static tunnel) or absent (eyes closed condition). The finding that postural atypical behavior is no longer observed in older participants is in accordance with the fact that reduced prevalence of motor deficits (fine motor control and programming) in older children with autism spectrum disorder has been observed, whether

through natural progression, results of interventional therapy, or the combination of the two (Ming et al. 2007).

The fact that hypo-reactivity (i.e., less postural perturbation) to a sway-inducing visual environment was only manifested for the highest oscillation frequency (0.50 Hz) for PP and the same tendency for BS suggests that our younger autistic participants seem not to have synchronized normally to the fastest stimulation frequency whereas they were able to do so for lower frequencies; in other terms, autistic participants were able to integrate and translate most sensory information into an appropriate motor response under most experimental conditions except when the processing and integration of fast visual stimuli was required. These results are consistent with the ''visual-motion integration deficit'' (Gepner and Mestre 2002a) and/or the ''temporo-spatial processing disorder'' (Gepner and Féron 2009), hypotheses proposing that atypical postural reactivity in autism is specific to fast moving visual stimulation (Gepner et al. 1995; Gepner and Mestre 2002a). Additionally, the finding that postural behavior in the autism group was comparable to that of controls for the lower velocities argues against the suggestion that atypical postural behavior in autism is due to motion perception impairments (Gepner et al. 1995), as a generalized motion perception deficit would predict atypical reactivity across all oscillation frequencies assessed, since the visual environment induced frequency-dependant sway for most conditions in the autism group. This finding is especially pertinent since the frequency-contingent autistic behavior occurred within an identical dynamic visual environment in all frequency conditions (except for its velocity level), and cannot be explained by inattention to stimuli, given the immersive character of the virtual visual environment and the small intra-subject variance between the 3 trials at each frequency. In addition, although there is some evidence of *motion perception* impairments in autism under specific experimental conditions (Bertone et al. 2003; see Bertone and Faubert 2006; Kaiser and Shiffrar 2009 for reviews), it is unlikely that such subtle perceptual deficits alone would translate into the atypical postural behavior observed in this study, given the intensity of the high-contrast information defining the virtual tunnel.

The present study demonstrated that the postural behavior of autistic participants differed under specific conditions of visual stimulation (i.e., higher oscillation frequencies), suggesting an association between perceptual environment and subsequent behavior. This association can be translated into real-life situations where temporally-changing visual environments are actively produced by behaviors often manifested by persons with autism that include: visual rotation induced by repetitive spinning movements and periodic visual stimulation induced by periodic hand or finger movements in the visual field. Whereas spinning behaviours are a reliable part of the autistic phenotype (Bracha et al. 1995), atypical lateral fixations are associated with produced or searched periodic movements (Mottron et al. 2007). The production of periodic body movements by autistics has generally been interpreted as the semi-voluntary behaviour implicating a vestibular input within a framework of atypical sensory modulation (Ornitz 1974). However, our findings suggest that any explanatory model for atypical body movements in autism should consider a possible decoupling between non-visual and visual systems under certain conditions of dynamic visual stimulation. Anecdotally, this suggestion is supported by the frequently reported behavioural observation that prolonged rocking, spinning and whirling behaviours in autism do not result in dizziness (Ornitz 1974; Grandin 1996).

Indeed, our findings demonstrate the impact that sensory anomalies can have on the everyday life functioning of persons with autism. In addition to postural anomalies, one can easily call to mind other examples of how other atypical sensory sensitivities can influence behaviors and health, e.g., hypersensitivity to certain food textures can impact on the eating habits of a person with ASD and, in turn, affect his/her health. Although sensory anomalies have long been reported (Ornitz, 1974), they were until recently considered as being associated features of ASD and not central to its diagnosis, and the focus was mainly placed on communication difficulties and other cognitive and behavioral features. Fortunately, there has been a recent shift of paradigm in the diagnosis of ASD; indeed, in the latest edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-V), [*Hyper-or hypo-reactivity to sensory input or unusual interest in sensory aspects of environment]* are now part of

diagnostic criterion B [*"Restricted, repetitive patterns of behavior, interests, or activities"*] (http://www.autismconsortium.org). Many now feel sensory anomalies to be a very important consideration as they are the root of many limitations in individuals with ASD; some therapies are focused on working through sensory systems as a premise for improving higher level functions such as language. Examples of such therapies include the Sensory Integration therapy (providing controlled therapeutically designed sensory experiences to which a child responds with adaptive motor actions), the Sensory Stimulation Techniques (providing passive sensory stimulation through a circumscribed modality, such as touch pressure, or vestibular stimulation), and Visual Therapies, e.g., oculomotor exercises and the application of ambient prism lenses and colored filters (for a review, see Baranek, 2002).

We believe that our findings enhance our understanding of autism-specific sensory anomalies in that it highlights the importance of chronological age and sensory stimulus specific features in the manifestation of atypical responses to sensory information. Hence, one should be cautious to neither over-emphasize, nor underestimate sensory anomalies within the context of autism diagnosis. Finally, findings from this study are specific to participants diagnosed with autism who have an IQ comparable to that of typically-developing persons. It is unknown whether this pattern of results transfers across the autism spectrum (e.g., Asperger syndrome or Pervasive Developmental Disorder not Otherwise Specified), but it would nonetheless be interesting and feasible to broaden our investigation of this diverse population, especially given the fact that the fully immersive and passive nature of the *Virtual Tunnel Paradigm* makes the assessment of children with limited language and cognitive ability possible.

Visually-Driven Postural Control in Children with a mTBI

The fourth and last study consists in a short report of preliminary results concerning the visually-driven postural control alterations in young individuals (9 to 18 years of age) having sustained a mild traumatic brain injury, as a function of visual stimulation velocity, severity of post-traumatic symptoms, and time post-injury. It was hypothesized that children with an

acquired alteration to the CNS, having sustained mTBI, would show more postural reactivity (BS and PP) compared to their controls, that this over-reliance on vision to control posture following mTBI would be observed up to 3 months post-injury, and that this would be linked to total score of self-reported post-traumatic symptoms at the moment of testing. Hence, postural reactivity (PP and BS) was measured for a Moderately Symptomatic mTBI group (MS-mTBI), a Low-Symptomatic mTBI group (LS-mTBI), and a Control one in response to the virtual tunnel oscillating at 3 different frequencies at 2 weeks, 12 weeks, and 12 months post-injury. Akin to what was hypothesized, preliminary results showed that at 2 weeks post-injury, the MS-mTBI group exhibited significantly more postural perturbations than the Control group, notably when the tunnel was static; that at 12 weeks post-injury, the MS-mTBI group continued to show significantly more postural perturbations than the Control group under most of the dynamic tunnel stimulation conditions, but not when the tunnel did not move (interestingly, only 11% of the participants in the MS-mTBI group were still significantly symptomatic at that time); and that the differences documented at 2 and 12 weeks were no longer observed at 12 months post-injury.

This pattern of results suggests that children, having sustained a mTBI and who are initially moderately symptomatic show, on average, increased postural instability when exposed to optic flow stimuli, particularly at 12 weeks post-injury, even when an elevated total score of symptoms is no longer self-reported and that this instability appears to resorb within 12 months post-injury. This indicates that the balance difficulties frequently reported following mTBI may, at least partially, be related to altered processing of dynamic visual information and do not appear to be solely and effectively predicted by the total score on a post-concussion symptoms scale PCS-R (Lovell & Collins, 1998). We can also advance the hypothesis that alteration in GABA neurotransmission following TBI, therefore reducing afferent sensory inhibition, could partially explain our results; GABA dysfunction has been documented using an animal model of TBI (Raible, Frey, Cruz Del Angel, Russek, & Brooks-Kayal, 2012) but also in pediatric human patients with TBI (Pangilinan, Giacoletti-Argento, Shellhaas, Hurvitz, & Hornyak, 2010).

These findings could have implications with regards to the clinical management of mTBI patients, since return to the practice of sports or other physical activities is often decided upon symptoms resolution (McCrory et al., 2005). Note that the postural data using the *Virtual Tunnel Paradigm* are part of a larger research protocol (with the same participants) that includes psychophysical and EEG measures in response to moving visual stimuli, neuropsychological testing, as well as some data obtained using clinical balance tests, i.e., the BOT2 (Bruininks-Oseretsky Test of Motor Proficiency, 2nd Edition) and the BESS (Balance Error Scoring System). Thus, it shall be interesting to compare the postural findings using the CAVE with those using clinical balance tests (Gagnon, Swaine, Friedman, & Forget, 2004) in order to evaluate whether the latter capture the balance difficulties with the same sensitivity as the Virtual Tunnel Paradigm. It would also be interesting to analyze the psychophysical measures as well as electrophysiological ones associated with the processing of visual motion so as to better discern the etiology of the observed visually-induced postural alterations in our symptomatic mTBI group compared to the Control group. Indeed, a study conducted in our laboratory (Brosseau-Lachaine, Gagnon, Forget, & Faubert, 2008) has shown that children with mTBI present selective processing deficits for higher-order visual information (complex 2nd order stimuli) information and that this deficit persists over relatively long periods post-injury (12 weeks). Furthermore, another study conducted by our team revealed anomalies in visually evoked potentials in response to complex visual stimuli (textures segregation) following mTBI (Lachapelle, Ouimet, Bach, Ptito, & McKerral, 2004).

Postural System Complexity and Neurobiological Considerations

In our study on healthy aging, we hypothesized that the complexity of the stimuli to be processed and integrated by the central nervous system increased in the dynamic compared to the static conditions, and may have more considerably challenged the postural control system of the older participants, thereby creating a saturation of this system and, consequently, the emergence of sub-optimal patterns of motor output (greater PP and BS).

The postural control system is a complex and extensive one. A good example of this fact is that evidence by our team has shown that during a learning paradigm, maintaining a simple upright stance somehow interacts with dynamic scene processing, making the task more complex (Faubert & Sidebottom, 2012). In this study, professional athletes were either in a standing or sitting position while they were learning to process a complex dynamic scene task; findings showed that the two groups differed remarkably in their learning functions, where the standing group improved at the task at a much slower rate than their sitting counterparts. In a similar study by Lemieux et al., (2013), performance on visuo-motor learning task was significantly diminished when participants were standing versus when they were sitting. This supports the notion that neural circuits required to process dynamic scenes, and the mechanisms necessary for maintaining upright quiet stance, interact in a significant way. Moreover, visuo-motor processing that underlies postural regulation requires the activation of many brain areas as was demonstrated in a study by Slobounov et al. (2006) which 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. They also observed the activation of prefrontal and parietal areas bilaterally which they believed was due to fronto-parietal networks for attentional modulations. They suggested 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 also 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, among other things, for attention control.

We believe that the very complexity of the postural system is what makes it so dynamic across time and vulnerable to alterations. Indeed, it is quite probable that the development and wiring of these brain subsystems takes time to mature and our data suggest that this would occur, at the earliest, at around 16 to 19 years of age and then begin a decline in efficiency starting at around 60 years of age. In other terms, in typical development, the brain may be acquiring higher complexity and optimization of the neural networks, whereas these would progressively become less optimal and less "complexity-friendly" at advanced ages. Furthermore, it could be argued that in atypical development, such as in autism, there is a lag in the maturation of the complex postural system but that it finally catches up at the critical phase of sensorimotor development, that is after 16 years of age. It is worth noting that in our study, autistic participants were able to integrate and translate most sensory information into an appropriate motor response under most experimental conditions except when the processing and integration of fast visual stimuli was required, i.e., the most complex stimulus as it is the fastest one. This theory is consistent with previous findings from our laboratory in which motion sensitivity in individuals with autism was dependent on stimulus complexity (Bertone, Mottron, Jelenic, & Faubert, 2003).

Finally, the aforementioned complexity hypothesis could also be applied to our findings concerning children with mTBI. Indeed, it is probable that the diffuse nature of the cerebral insult somewhat perturbs the complex networks underlying postural control, at least momentarily. An interesting behavioral and neuro-structural parallel can be drawn between our healthy aging and our mTBI participants: they both manifest an over-reliance on visual dynamic cues when regulating posture and they both show some kind of diffuse axonal changes. Indeed, one can easily imagine how diffuse axonal changes can impact both cortico-cortical and cortico-subcortical communication and, consequently, posture. Studies have reported changes in white matter in: healthy aging (Madden, Bennett, & Song, 2009; Raz & Rodrigue, 2006), as well as diffuse axonal injury, metabolic impairment, alterations in neural activation and cerebral blood flow perturbations in children with mTBI (Choe, Babikian, DiFiori, Hovda, & Giza, 2012), and white matter changes in the corpus callosum of adult

concussed athletes up to 6 months post-concussion (Henry et al., 2011). Graham (1996) proposed that it is the extensive and diffuse nature of the axonal injury that is responsible for the balance deficits observed after severe TBI and that diffuse damage contributes to the disruption of mechanisms responsible for the appropriate sensorimotor integration required for the maintenance of balance. Likewise, work by Shumway-Cook and Olmscheid (1990) suggests that persons with severe TBI have sensory integration problems (as was previosuly mentioned) and that these problems are manifested by an increase in postural sway in conditions of reduced or conflicting sensory inputs.

Postural Control and Cognition

Given the fact that postural control system is a complex and energetically demanding one, it is not surprising that cognitive tasks interfere in a significant way with the maintenance of upright stance. For example, studies have shown that when performing a learning visuo-motor task, being in a standing position importantly hinders learning performance of the task compared to performance while in a sitting position; this phenomenon was demonstrated in healthy older adults (Lemieux et al., 2013) but also in professional athletes, an expert population in visuo-motor tasks (Faubert & Sidebottom, 2012). Moreover, it has been shown that sensory integration in postural control requires attention as demonstrated by increased instability in standing healthy subjects when concurrently asked to perform an inhibitory reaction time task (Redfern, Jennings, Martin, & Furman, 2001). Slobounov et al. (2006) also suggested that there is a functional interaction between modality specific posterior-visual and frontal–parietal areas that subserve visual attention and other perceptual-motor tasks.

Although difficult to ascertain in the present studies, it is possible that the decreased cognitive functioning in mTBI (Levin et al., 2013), autism ((Maister, Simons, & Plaisted-Grant, 2013) and aging (Hartley, 2001) has an influence on postural control efficiency, as it can be argued that performing cognitive tasks require more brain resources in these populations, therefore leaving less resources for the task of postural control.

In our everyday lives, we often perform cognitive tasks while maintaining posture (e.g., working memory: calculating the cost of a purchase while waiting in line in a supermarket; thinking about dinner planning, etc...), thus, passively standing within the Virtual Tunnel Paradigm, although efficient and useful in measuring visually induced postural reactivity across populations, does not entirely account for the real-life demands on the postural control system. Future studies should look at performances on the Virtual Tunnel Paradigm while performing increasingly difficult cognitive tasks (e.g., mental calculus) but also in using other experimental paradigms mimicking the complexity and richness of the real world visual environment.

Study Limitations and Future Directions

Other factors aside from age could have affected our results such as weight and leg length (Dutil et al., 2013; Schmuckler, 1997), physical activity history, fatigue levels during testing (Robillard, Prince, Filipini, & Carrier, 2011), etc... This being said, we believe that the sensitivity and ecological validity of the immersive virtual reality technology used in our studies combined with the wide range of ages and diversity of the populations tested have helped us to shed some light on the visually-driven postural reactivity in developing and aging humans with regards to upright stance. Not only have we learned about the maturation and aging of the systems underlying sensorimotor integration involved in postural control with healthy participants, but we have also showed the feasibility of using the *Virtual Tunnel paradigm* as a potential sensitive and specific assessment tool that may help guide the diagnosis and clinical management of clinical populations (autism, mTBI, etc...). It would be very interesting to investigate visually-driven postural regulation using the same paradigm on other populations with developmental disorders (e.g., Down Syndrome, Cortical Dysplasia, etc...), neurological/ neurodegenerative conditions (epilepsy, Parkinson's disease, multiple sclerosis, Alzheimer's disease, etc...), and in pathological aging populations (e.g., older adults with autism or with TBI), to name a few.

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