Virtual environments and sensory integration: Effects of aging and stroke

Nicoleta Bugnariu¹, Joyce Fung², ³
¹Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada
²School of Physical and Occupational Therapy, McGill University, Montreal, Quebec, Canada
³Jewish Rehabilitation Hospital, Laval, Quebec, Canada

Research was carried out on the effects of aging and sensory motor deficits following strokes with respect to the capacity of the central nervous system to resolve sensory conflicts created by Virtual Reality (VR). The results of this research demonstrate that VR can be a valuable tool for therapeutic interventions that require an adaptation to complex, multimodal environments. The rehabilitation protocols include balancing training in virtual environments.

Les études qui ont été menées sur les effets du vieillissement et des déficits sensori-moteurs consécutivement aux accidents vasculaires cérébraux concernent la capacité du système nerveux central à résoudre les conflits sensoriels créés par la Réalité Virtuelle (RV). Les résultats de ces études ont démontré que la RV peut être un instrument valable en tant qu’intervention thérapeutique ce qui requiert l’adaptation aux environnements multimodaux complexes. Les protocoles de rééducation comportent des exercices d’équilibration dans les environnements virtuels.

Introduction

Loss of upright balance control resulting in falls represents a major health problem for older adults and stroke survivors. Postural imbalance may arise not only from motor or sensory impairments but also from the inability to select and reweight pertinent sensory information. This chapter discusses the use of virtual environments to investigate basic mechanisms of sensorimotor integration. In particular, the effects of age and stroke on the ability of the central nervous system to resolve sensory conflicts and maintain balance will be addressed. Results from two main studies will be presented to focus on the current use and beneficial potential of implementing rehabilitation protocols that include balance training in virtual environments.
1 Background

1.1 Balance control

One of the most challenging aspects of rehabilitation is the regain of balance control. The task of postural control involves controlling the body’s position in space for the dual purposes of stability and orientation. It requires the integration of sensory information to assess the position of body in space and the ability to generate forces for controlling body position. Postural control requires a complex interaction of musculoskeletal and neural systems. Musculoskeletal components include joint range of motion, spinal flexibility, muscle properties and biomechanical relationships among linked body segments. Neural components essential to postural control encompass sensory and motor processes, as well as cognitive planning and higher level processing essential for adaptive and anticipatory aspects of postural control. Sensory processes encompass the visual, vestibular and somatosensory systems, sensory strategies that organize these multiple inputs and internal representations important for the mapping of sensation to action. Motor processes include neuromuscular response synergies and the selection and sequencing of muscles to be activated. Adaptive or reactive postural control, also referred to as feedback control, involves modifying sensory and motor systems in response to changing tasks and environmental demands. Anticipatory aspects of postural control, also referred to as feedforward control, pre-tune sensory and motor systems for postural demands based on previous experience and learning.

The maintenance of upright equilibrium is essentially a sensorimotor integration task. The central nervous system (CNS) has to generate task-specific and goal-directed complex motor responses based on the selective and rapid integration of sensory information from multiple sources. Since each sensory system has its own coordinate framework, specific time delay and reliability, sensory conflicts may arise and represent situations in which the CNS has to recalibrate the weight attributed to each particular sensory input. Humans can tread on changing and uneven terrains without falling because the intact CNS can make ongoing corrections.

Research has shown that in quiet stance with feet together, balance in the sagittal plane is achieved mainly by the control of ankle torque whereas balance in the frontal plane is predominantly controlled by changing hip torque [WIN 96]. Previous research on multidirectional surface translations showed similar control mechanisms with complex central and peripheral organization of the postural responses [HEN 98 a, b]. Unexpected movement of a support surface elicits rapid, automatic and coordinated postural responses that are triggered primarily by somatosensory afferents depending on the velocity and direction of perturbations [DIE 88; ING 95; RUN 98; FUN 05]. These responses are not merely segmental reflexes organized at the level of the spinal cord, but rather depend on the integration of proprioceptive, visual and vestibular information at many levels of the neuraxis [FUN 05; MAC 99; HOR 96].

1.2 Contribution of sensory systems and their interactions

Effective postural control requires more than the ability to generate and apply forces for controlling the body’s position in space. In order to know when and how to apply restoring forces, the CNS must have accurate information of where the body is in space and whether it is stationary or in motion. Somatosensory afferents, including mechanoreceptors, pressure receptors, muscle spindles, Golgi tendon organs and joint receptors, provide information regarding the body’s position and motion in space with respect to the support surface. Visual
inputs provide information concerning the position and motion of the head with respect to the surrounding environment. With the semicircular canals sensing angular accelerations of the head in different planes and the otoliths signaling linear position and acceleration of the head with respect to gravity and inertial forces, the vestibular system provides a gravito-inertial frame of reference for postural control. Somatosensors, being distributed throughout the body, are critical for determining the orientation and configuration of the body segments. In contrast, visual and vestibular receptors are located in a head that moves independently from the trunk and limbs. Therefore, body configuration and orientation information from head-based sensors is either limited, or must be derived. Somatosensory information from the lower extremities and trunk is particularly important for maintaining balance when the subject maintains contact with a large, rigid, and stable support surface [HOR 96]. Recent modeling studies have provided a scheme of coordinate transformations such that head-based sensors are mapped downwards from neck muscles to leg muscles, whereas somatosensory afferents from the feet and legs are mapped upwards to the trunk [MER 97].

It was once thought that visual inputs were too slow to have any effect on the rapid response due to sudden perturbations of stance, since the sensation of motion induced by moving visual fields has a relatively long latency (~1 s), and the influence on body sway is too slow [NAS 78]. Subsequent experiments have shown that visual information that conflicts with those arising from other sensory channels can have a rapid and profound effect on postural responses [VID 82; KES 04a]. For instance, when visual inputs are stabilized with respect to the head during the time of the perturbation only, the initial triceps surae burst can be significantly attenuated and forward sway increases. In contrast, merely closing the eyes during a postural perturbation has no effect on the early evoked response or the performance, suggesting that sensory context is an important factor in shaping the strategy for postural responses [VID 82]. Absence of vision under these conditions does not compromise postural performance since other sensory channels provide sufficient information. In contrast, visual information that conflicts with that from other sensory channels can have a rapid and profound effect on postural responses. An example of such sensory conflict can be experienced when riding a bus while watching the traffic outside the window and for a brief period not knowing for certain if it is the bus that is moving forward or the traffic moving in the opposite direction. If the bus is moving, certain postural muscle activation commands are necessary in order to maintain balance. If the bus is stationary and the illusion of movement comes from the moving traffic, then the same postural commands would be inappropriate. The influence of moving visual fields on postural stability depends on the characteristics not only of the visual environment, but also of support surface, including size of the base of support and its rigidity or compliance [STR 06; KES 04b].

Within physiological limits, a central recalibration process exists to produce appropriate responses even in the presence of sensory conflicts, as for example when the visual information is discordant with the information provided by the somatosensory system. The following studies will present data from experiments that used virtual reality technology in order to study the mechanisms of sensory integration, the ability of the CNS to resolve sensory conflicts and maintain balance.

1.3 Virtual reality and rehabilitation

The current state of knowledge in rehabilitation emphasizes the need for intense task-related practice to promote the re-acquisition of balance skills. Motor learning is promoted by factors such as changing environmental contexts, alterations in the physical demands, problem solving, random presentation of practice tasks, sufficient practice and patient empowerment.
Virtual reality (VR) refers to a range of computing technologies that present a 3D interactive simulation that occurs in real-time and presents artificially generated sensory information (from vision and proprioception) in a form that can be perceived as similar to real-world objects and events. Virtual reality is a valuable tool for therapeutic interventions that require adaptation to complex, multimodal environments [KES 04b]. VR technology with the capacity of simulating environments offers a new and safe way to not only increase practice time but also to offer the varied environments and constraints needed to maximize learning. Moreover, the “hi-tech” nature of the practice itself can be a further motivation for the subjects. The term virtual ‘environment’ or VE is used to describe the simulation of a visual 3-D environment presented to the subject via a monitor, a large screen, or through a helmet-mounted display (HMD). In a VE, the simulated objects and events are not only sensed, but the user can anticipate and react to them as though they were real. The user often feels, at least to some degree, “present” in the simulated world, and this feeling of presence is arguably the defining feature of the VR experience. VR systems have been applied to the training of upper and lower extremities after stroke [HOL 99; DEU 01], to improve mobility in persons with impaired spatial abilities or to train balance control [McC 02, SVE 04] and in vestibular rehabilitation [WHI 02].

2 Methodology

The common methodology described below was used in both studies to investigate the effects of aging and stroke on the capability of the CNS to select appropriate sensorimotor strategies and regulate balance while under conditions of sensory conflicts created by VR. We also aimed to determine the effect of repeated exposures to VR on the ability of the CNS to resolve sensory conflicts (Figure 1).

**Procedure.** During quiet stance, subjects were exposed to random visual and/or surface perturbations consisting of ramp-and-hold tilts of 8° (peak velocity of 36°/s) in each direction of the pitch and roll planes. Visual perturbations were induced by sudden movements of a virtual environment (VE) viewed through a helmet-mounted display (HMD, Kaiser Optics ProView™ XL50, with a field of view of 50° diagonal, 30° vertical x 40° horizontal). The VE consisted of a 3D rendered computer-simulated room generated by SoftImage XSI on a CAREN 2.3.0 Workstation (Motek Inc) and complete with windows, columns, flooring and ceiling textures. The perturbations consisted of: 1) visual-only, the VE was tilted but the surface was stationary; 2) surface-only, the surface was tilted but the VE was fixed; 3) discordant, visual perturbation was combined with synchronized surface perturbation in the same direction, and 4) concordant, visual perturbation was combined with synchronized surface perturbation in the opposite direction resembling the real life perception.

The support surface was mounted over a six-degree-of-freedom motion base servo-controlled by six electrohydraulic actuators [FUN 98]. The initial stance posture consisted of weight evenly distributed between feet placed on 2 force-plates (AMTI OR6-7), heels 15 cm apart and feet oriented in a 15° toe-out position. Subjects were instructed to maintain balance to the best of their abilities without taking steps where possible. If a step was taken, the subjects were instructed to resume the initial stance posture. A total of 72 perturbation trials were completed for a minimum of 1 hour VE immersion.

**Data recording.** A six-camera VICON 512 system (Oxford Metrics) was used to capture 3D position data at 120 Hz from 36 retroreflective markers placed over anatomical landmarks and 4 markers placed on the movable platform. Ground reaction forces and moments from the force-plates were acquired at 1,080 Hz.
Eight bilateral muscles were instrumented with bipolar Ag-AgCl surface electrodes to record electromyographic (EMG) signals using a Noraxon system: tibialis anterior (TA), gastrocnemius medialis (MG), vastus lateralis (VL), semitendinosus (ST), tensor fascia latae (TFL), erector spinae (ES) at the L3 level, neck extensor (NE) and neck flexor sternocleidomastoideus (SCM). EMG signals were amplified, digitized, band-pass filtered (10–400 Hz low-pass) and sampled at 1,080 Hz. EMG signals were further full-wave rectified and lowpass filtered at 100 Hz during offline analysis. Functional balance and mobility in terms of gait velocity, ability to maintain tandem stance, timed repeated sit-to-stand, as described in a physical performance battery [GUR 00] were assessed before and after VE exposure and perturbation trials.

Data analysis. A biomechanical model (Plug-In Gait) was used in conjunction with kinematic data and anthropometric measures to calculate the displacement of the body’s center of mass (COM). Resultant center of pressure (COP) in the horizontal plane was calculated as the weighted sums from the vertical force and anteroposterior (A/P) and mediolateral (M/L) moments from the individual force plate. Inertial components in forces and COP data due to movement of the support surface were corrected as described previously [PRE 04]. Muscle latencies were determined as the first burst that exceeded a threshold of two standard deviations above the background mean level and lasting at least 50 ms, with an activation probability of at least 50%. Data from different trials of each individual were ensemble-averaged across each one of the four testing conditions (vision only, surface only, discordant and concordant) and each one of the directions of pitch (toes-up/down) and tilt (left/right-down). These averages were pooled to produce a population average (young, old, stroke) for each direction of perturbations and condition of testing. To estimate the ability to adapt, average responses form the first 10 and last 10 trials were also calculated and compared.
3 Effects of aging

Aging is associated with the decline in the integrity of many postural regulating systems and these age-related changes in musculoskeletal, sensory systems, neural processing and conduction of information could all potentially impact on postural control in older adults [HOR 89; MAC 89; MAK 96]. The health care costs associated with seniors’ falls are estimated at 1 billion dollars annually. The effects of aging and repeated exposures on the capability of the CNS to select pertinent sensory information and resolve sensory conflicts were investigated with virtual reality in the present study.

3.1 Subjects

Ten young adults (5 males and females of mean age 26±5.1 y.o.) and 10 older adults (5 males and females of mean age 72 ±3.3 y.o.) participated in this study. Subjects were healthy with no neurological problems, musculoskeletal conditions or motion sickness.

3.2 Results

3.2.1 Kinematics

Representative examples of COP and COM traces (thin and thick lines, respectively, left-sided graphs), as well as group averages of COM (right-sided bar graphs) during pitch and roll perturbations are shown in Figures 2 and 3, respectively. During visual-only perturbations, minimal displacements of COP and COM were observed in both subject groups. Surface perturbations, with or without visual perturbations, provoked displacements of COP and COM first in the direction of the perturbation, and then reversed to oppose the perturbation for balance adjustment. Changes in COP always preceded and encompassed those of COM. In young adults, COP and COM displacements were smallest during perturbation where the visual and somatosensory stimuli were concordant. The displacements were markedly larger in older adults and took longer duration to return to the neutral positions. In older adults, during surface-only and discordant perturbations, COM and COP excursions increased substantially and took longer or never return to a neutral or stable position.

During visual-only perturbations, similar and minimal (2-10 mm) postural sway was observed in both the young (gray) and old (black) groups of subjects (bar graphs, Figures 2 and 3). In general, across all other conditions of testing, older adults displayed significantly larger COM peak-to-peak excursions (20 to 40 mm more than young adults). The presence of sensory conflicts in surface-only and discordant perturbations induced significantly larger COM excursions than concordant perturbations in both young and old adults. However, the presence of sensory conflicts required a larger correction in older adults. During surface-only perturbations, mean COM excursions for older subjects compared to young were 10-15 mm larger in pitch (Figure 2) and 15-25 mm in roll (Figure 3) perturbations. During conditions of discordant perturbations, COM excursions were 30-50 mm and 20-40 mm larger in old subjects compared to young during pitch (Figure 2) and roll (Figure 3) perturbations. During conditions of concordant perturbations, COM excursions were not significantly different between old and young subjects. The average COP values (not shown) displayed similar trends, although always larger in range as compared to the COM.
Fig. 2. Pitch plane COP and COM responses in different sensory conditions. Representative example of individual traces of COP (thin lines) and COM (thick lines) from one young and one old subject (left panel) exposed to toes-up tilt of the surface. Bar graphs on the right panel show COM peak-to-peak excursions (mean ± S.D.) averaged across 10 young subjects (gray bars) and 10 older subjects (black bars) in both toes-up (left column) and toes-down (right column) directions.
Fig. 3. Roll plane COP and COM responses in different sensory conditions. Representative example of individual traces of COP (thin lines) and COM (thick lines) from one young and one old subject (left panel) exposed to right-down roll of the surface. Bar graphs on the right panel show COM peak-to-peak excursions (mean ± S.D.) averaged across 10 young subjects (gray bars) and 10 older subjects (black bars) in both left-down (left column) and right-down roll (right column) directions.

3.2.2 EMG activity

The average EMG latencies of ventral muscles responding in the toes-up pitch direction during surface-only, discordant and concordant perturbations in young and old adults are shown in Figure 4. Young subjects showed similar latencies from the first 10 to the last 10 trials, and thus are averaged across all trials of similar conditions (Figure 4, gray circles). Old subjects showed increasingly earlier activations from the first 10 (Figure 4, black diamonds) to the last 10 trials (Figure 4, open triangles). No muscle activation was observed in young adults during visual-only perturbations. In old adults, sporadic muscle activations were present during visual-only perturbation but the activation probabilities of 50% was not reached, and thus were not included further in the analysis. In young adults, muscle recruitment generally...
followed a distal-to-proximal sequence, regardless of perturbation direction or sensory conflicts. The ankle muscles, TA and MG, were first to be activated during toes-up and toes-down tilt, respectively, at a latency of 80-100 ms. VL and ST were activated 110-130 ms, followed by TFL and ES approximately 30-50 ms later, while the neck muscles SCM and NE were activated slightly earlier at 150-170 ms.

Fig. 4. Single-session adaptation of muscle responses. EMG latencies (mean ± S.D.) of ventral muscles responding to toes-up pitch surface perturbations across young (gray circles) and old subjects. Note the decrease in the latencies in old subjects from the first 10 (black diamonds) to the last 10 (open triangles) trials.
In older adults, the distal-to-proximal sequence of EMG activation was less consistent, especially under sensory conflicts, during surface-only and discordant perturbations (Figure 4, black diamonds), where a reverse sequence was observed. In some older subjects, following discordant visual and somatosensory stimuli, activation of neck muscles preceded distal leg muscles by 25-70 ms. Generally, the EMG onset latencies of older adults, which were already delayed as compared to young adults, were further prolonged in conditions of sensory conflicts. However, adaptation occurred during the one-hour session such that ankle EMG latencies were 20 ms shorter in the last 10/72 perturbations as compared to the first 10 trials.

Conflicting visual and somatosensory stimuli modulate automatic postural responses in both healthy young and old adults but the presence of sensory conflicts had a larger impact on the selection of appropriate strategies for balance control in older adults. When the VE was manipulated to provide distorted visual perception, i.e. during surface-only or discordant perturbations, older adults took more steps, had longer EMG onset latencies as well as larger COP and COM excursions. Postural instability as measured by COM excursions increase markedly especially during discordant perturbations. Similar age-related postural instability was also reported by Mahboobin et al. [MAH 05] who showed that optic flow induced larger postural responses in old subjects than in subjects who had adapted from unilateral loss of vestibular function. It is plausible that delayed or diminished vestibular and somatosensory inputs in older adults increases their sensory thresholds to complex multimodal stimuli, thereby inducing a greater reliance on visual inputs and making it more difficult for them to respond selectively to visual and physical destabilization. Excessive reliance on visual input may be a natural compensatory strategy to cope with poor balance in seniors, but it can be problematic when the visual information is not reliable.

Visual-only perturbations elicit minimal postural responses in both young and old subjects with only sporadic activations of muscles in older adults, suggesting that under normal circumstances when there is a stable support surface, the somatosensory information is weighted more in regulating upright posture. The use of HMD to deliver the visual perturbation might have also limited the influence of visual inputs. Postural responses coupled with optic flow are less frequent when the optic flow is delivered in a central field of view, like the HMD, as compared to BNAVE display with a full field of view [WHI 02; SPA 06]. The influence of moving visual fields on postural stability depends on the characteristics not only of the visual environment, but also of the support surface, including the size of the base of support and its rigidity or compliance [AMB 89]. Somatosensory information from the lower extremities and trunk is particularly important for maintaining balance when the subject maintains contact with a large, rigid, and stable support surface [HOR 96]. Surface-only perturbations present a postural challenge for both young and old. EMG onset latencies can be delayed and prolonged, while postural sway increases, as compared to concordant visual and somatosensory perturbations. Similar effects of visual stabilization were observed on initial bursts of ankle muscles [KES 04a].

4 Effects of stroke

Sensory and motor impairments following cerebral vascular accidents can lead to poor control of balance and mobility. The motor areas of the cerebral cortex are involved in the preparation of voluntary movement, however, their role in postural mechanisms, and in particular, in response to unexpected perturbations of stance is uncertain [MAS 92]. Nevertheless, EMG analysis has revealed disordered patterns of muscle activity, including abnormal timing and sequencing of muscle activation as well as excessive cocontraction in
hemiplegic subjects reacting to external perturbations [DUN 87]. Some evidence has been provided on misrepresentation of trunk orientation in subjects with neurologic injury [LUY 97]. Hence, the central problem may reside in sensorimotor integration which involves coordinate transformations leading to a misinterpretation of the body in space. Stroke patients manifest altered postural adjustments to voluntary head motions during standing [LAM 03]. Stroke subjects have difficulty maintaining balance when exposed to perturbations during standing or walking and their responses are not modulated by the direction of perturbation or by the task requirement [FUN 03]. The Approximately two thirds of stroke patients are above 65 years old; therefore aging may introduce confounding factors for balance control after stroke. We examined the effects of aging and sensory motor deficits following stroke on the capability of the center nervous system to select pertinent sensory information and resolve sensory conflicts created by virtual reality.

4.1 Subjects

Six stroke patients 62 to 76 years old and six age-matched healthy old adults participated in this study. The patients were 7 to 27 months post stroke, had no neglect, and were able to ambulate independently, with an assistive device (cane) with a mean speed of 0.57 m/s (range 0.35 to 0.85 m/s).

4.2 Results

Representative examples of COP and COM traces (light and dark blue/red lines, for control/stroke patients respectively, left-sided graphs) are shown on Figure 5. Bar graphs on the middle panels show COM peak-to-peak excursions (mean ± S.D.) averaged across groups of subjects in both directions of perturbations. Bar graphs on the right panels show data differences between first and last 10 trials. The displacements of the center of pressure (COP) and body’s center of mass (COM) increased in the presence of sensory conflicts and neurological injury (p < 0.05).

4.3 Clinical measures

With repeated exposures to VR-induced sensory conflicts, a general training effect associated with less stepping responses and improved ability to maintain balance was observed in older adults. In healthy older adults, the last 10 out of 72 perturbation trials had significantly reduced COP and COM excursions as compared to the first 10 perturbations. The differences between first and last 10 trials, although present were less evident in stroke subjects. The ability to anticipate the physical constraints of the environment and adapt the balance behavior accordingly is the result of intricate sensorimotor integration. The cognitive processes range from correctly perceiving and interpreting information from different body sensors (somatosensory, vestibular and visual) to planning and coordinating the effectors appropriately to produce the desired movement. The average number of steps taken by older subjects also decreased from 3 during the first 10 trials to one in the last 10 trials (p < 0.001). At the end of the 1h immersion in the VE and repeated exposures to sensory conflicts perturbations, four old adults scored 1-2 points higher on their ability to maintain tandem stance (p < 0.05). A loss of stepping response and reduced training effect was observed in stroke patients who did not step but relied on external support (harness). However, five out of six stroke patients improved by 10 sec the ability to maintain independent tandem stance position at the end of the 1h immersion in the VE and repeated exposures to sensory conflicts perturbations. It has to be noted that the standard test position during experiments was side by side and not tandem.
Maintaining tandem stance is a challenge for seniors and populations with decreased balance, and inability to do so is correlated with increased risk of falls [MAK 96]. Therefore, the improvements noted have clinical significance. No change was observed in gait speed and timed repeated sit-to-stand. All subjects tolerated well the use of the HMD with the exception of one older subject who reported mild discomfort due to the tight fitting. All subjects were able to complete the 1h immersion in the VE with no reports of nausea.

4.4 EMG activity

Representative examples of muscle activation sequence following toes up rotation in a healthy control subject (left panel) and in stroke patient non paretic side (middle panel) and paretic
Fig. 6. Muscle responses to perturbations in different sensory conditions. A: Example of muscle activation sequence following toes up rotation in a healthy control subject (left panel) and in stroke patient non paretic side (middle panel) and paretic side (right panel). B: Group Mean ± SD for muscles onset latencies following pitch rotations (toes-up) for healthy control subjects (blue) and stroke subjects (red) in different sensory conditions: surface only, concordant and discordant in left, middle and right panels, respectively.

Side (right panel) are showed in Figure 6A. Stroke subjects show under-activated responses on the paretic leg and exaggerated responses on the non-paretic limb.

The average EMG latencies of ventral muscles responding in the toes-up pitch direction during surface-only, discordant and concordant perturbations in stroke (red circles) and healthy old adults (blue diamonds) are shown in Figure 6B. Visual only perturbations produced sporadic muscles activations in both old adults and stroke patients. In general, aging disrupted the distal-to-proximal muscle recruitment sequence and the presence of sensory conflicts and stroke exacerbated the inconsistencies. Neck muscles were the first activated in both stroke and healthy age-matched subjects. EMG latencies of ankle and hip muscles that were delayed in stroke subjects as compared to healthy older adults during surface perturbations alone, were further prolonged by 40-60 ms in conditions of sensory conflicts.
Appropriate muscles need to be activated in order to change the forces exerted through the body and limbs in contact with the support surface. These motor responses are based on selective and rapid integration of visual, vestibular and somatosensory information [VAN 99]. As the sensory conditions changed from one trial to another, and sensory conflicts were present, an update of sensory weights to current conditions was necessary, so that motor commands were based on the most precise and reliable sensory information available [MER 05; JEK 06]. Reweighting mechanisms used to resolve sensory conflicts are not entirely understood. How the weights given to each sensory input are determined and how various factors influence this process remain open questions. It has been suggested that weighting depends on the sensory context (inconsistency between sensory signals) as well as on the subject [VAN 99; BRI 07]. A commonly used technique to study sensory integration and reweighting is to stimulate postural sway with visual and somatosensory stimuli and to determine the frequency-response function which described gain and phase. Linear, spectral analysis was performed for each trial by computing the individual Fourier transforms of the time series of COM postural displacements and of the stimuli motion, either visual or surface. For each one of the four sensory conditions, the frequency-response function was computed by dividing the transform of the estimated COM by the transform of the stimulus. The gain is the absolute value of the frequency-response function. For example, a surface gain value of one will indicate that the displacement of body in space is equal to the displacement of the support surface.

Figure 7 illustrates COM gain relative to the surface (open icons) and visual (filled icons) stimulus in young (blue), healthy old adults (red) and stroke patients (orange). In general, young adults displayed low visual gains and high values of surface gains. In conditions of visual-somatosensory conflict, they increased surface gain and decreased visual gain, suggesting that young adults deal with the sensory conflict by either attempting to suppress visual information altogether, or attributing more weight and increased reliance on somatosensory feedback. Healthy older subjects and stroke patients displayed higher visual gains than young adults regardless of the sensory conditions. Moreover, in conditions of sensory conflict, they
adopted an opposite strategy increasing the visual gain and lowering the surface gain. This demonstrates an excessive reliance on visual inputs or a need to first stabilize their head, a common strategy adopted by people with balance impairments.

Conclusions

We examined the effects of aging and sensory motor deficits following stroke on the capability of the center nervous system to resolve sensory conflicts created by VR. Virtual reality can be a valuable tool for therapeutic interventions that require adaptation to complex, multimodal environments. When designing VR protocols involving multisensory modalities one should be aware of the potential of sensory conflicts and their effects.

Conflicting visual and somatosensory stimuli can modulate automatic postural responses in both healthy young and old adults. Aging affects the interaction of the somatosensory and visual systems on the ability of the CNS to resolve sensory conflicts and to maintain upright stance equilibrium. Compounding effects of age and neurological injury can skew the sensory recalibration processes required for resolution of sensory conflicts toward an excessive reliance on visual inputs. The presence of sensory conflicts has a significantly larger impact on the regulation of balance in stroke subjects. By far the most challenging condition was created by the discordant perturbations with longest onset latencies of distal muscles, activation of neck muscles first and increased COM gain relative to the visual stimulus. This strategy was observed in both stroke and healthy age-matched subjects. It demonstrates an excessive reliance on visual inputs.

Visual dependence may be a compensatory strategy for coping with poor balance post stroke. In addition to motor impairment, postural imbalance in patients with hemiparesis may be caused not only by elementary sensory impairment (visual, somatosensory, vestibular) but also by the inability to solve sensory conflicts, to select pertinent sensory information. Excessive reliance on visual input may be a natural compensatory strategy for coping with poor balance in patients after stroke. The excessive reliance on vision may become problematic when the visual information is not reliable.

The resolution of sensory conflicts is affected by aging and stroke but can be enhanced by training. Repeated exposure to VR-induced sensory conflicts improves balance performance in all healthy older subjects and to some extent in stroke subjects. Even with a one-hour immersion in virtual environment and exposure to sensory conflicts, it is possible for the CNS to recalibrate and adapt to the changes. A training program of longer durations is needed to confirm sustainable long-term effects. Therefore, preventive and rehabilitation programs targeting postural control in seniors and stroke patients should take into account the possible impairment of sensory organization or sensorimotor integration and include exercises to be performed in different VE under conditions of sensory conflicts.

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