The Use of Visual Feedback Techniques in Balance Rehabilitation

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1 How Our Brain Uses Vision to Learn Novel Tasks

Vision supports achievement of a variety of goals of action, including transportation of the whole body to a new location, as in locomotion, and movement of a body part or limb to a new position, as in reaching and aiming. Visual feedback based correction of such goal-directed actions is a slow process that results in intermittencies because the processing of visual information is faster than the accompanying motor output corrections [1, 2]. To overcome this limitation of the on-line, closed loop processing of visual information, humans can also plan movements on the basis of visual cues. Thus, through short-term visuo-motor practice the motor system can learn novel visuo-motor transformations and apply them in order to predict future actions. This is because humans can pre-program movements based on predictable visual cues. Experience in a particular visuo-motor coordination task leads to the storage of appropriate control parameters which are used in programming subsequent movements, via a short-term motor memory [3]. This is the main principle visual feedback training is based on.

The coordination between vision and posture constitutes a familiar element in our daily life activity repertoire. The precise and incessant adaptation of posture and locomotion to visual cues is a complex task that requires the coordination of the body's multiple and often redundant degrees of freedom. The multiple degrees of freedom that need to be controlled can be a burden in accomplishing any complex visuo-motor transformation. In addition, the high mechanical resonance of the

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effectors involved in postural control imposes additional constraints in visuo-motor adaptation. Yet, visually driven postural control is highly relevant to the performance of daily actions that preclude the risk of falling.

2 The Design of Visual Feedback Systems

On-line visual feedback of the body's Centre of Gravity (CoG) and Centre of Pressure (CoP) position has powerful control mechanisms over static and dynamic postural sway. Based on the capacity of the postural control system to make use of the available visual information, assistive and training devices have been developed which provide augmented feedback during performance of voluntarily controlled postural sway actions [4]. A typical example of such a system is shown in Fig. 1. The individual performing the exercise is standing on a force platform which records the three components of the ground reaction force or the CoP position at a sampling rate of at least 100 Hz. This performance signal is visually represented and fed back to the standing subject with negligible time delay. In Fig. 1 the instantaneous CoP displacement is indicated by the continuous black line while the subject is instructed to voluntary shift his/her CoP over the pre-specified stationary visual targets, indicated here by the squares. Another example of a visual feedback practice

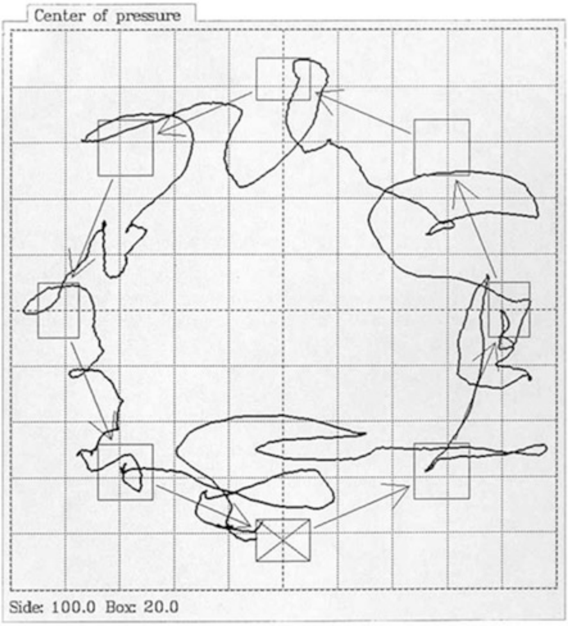


Fig. 1 A visual display of a visual feedback exercise protocol. The individual performing the exercise is standing on a force platform which records the CoP position. This performance signal is visually represented on a computer display with negligible time delay. The instantaneous CoP position is indicated by the continuous *black line* while the subject is instructed to voluntary shift his/her CoP over the pre-specified stationary visual targets, indicated here by the *squares*

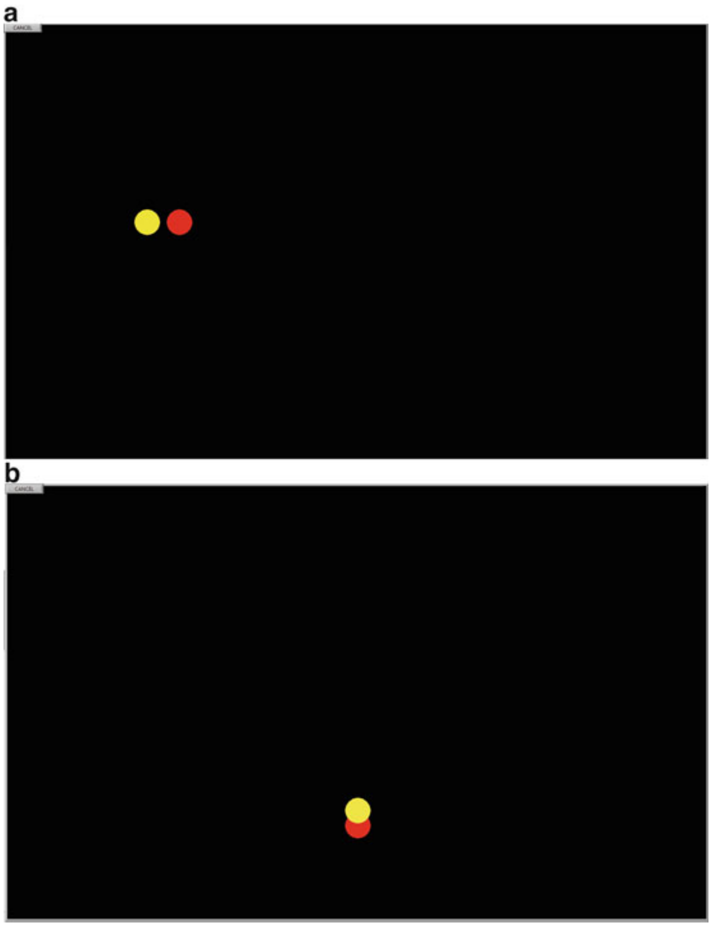


Fig. 2 Another example of a visual feedback practice protocol. The subject is instructed to track with his body the *red ball* as precisely as possible which moves in an oscillating pattern in either the horizontal (**a**) or vertical (**b**) direction. The *yellow ball* represents the instantaneous body weight (force) distribution between two force platforms while the subject is swaying between the two platforms (Color figure online)

protocol is illustrated in Fig. 2. Here, the subject is instructed to track with his body the red ball as precisely as possible which moves in an oscillating pattern in either the horizontal (Fig. 2a) or vertical (Fig. 2b) direction. The yellow ball represents the instantaneous body weight (force) distribution between two force platforms while the subject is swaying between the two platforms. Several commercially available systems such as the “Nintendo Wii” balance board are also based on the same training principle and have been extensively used in balance rehabilitation [5].

3 Does Visuo-Motor Learning Generalize to Other Actions?

One intriguing question is how well a learned transformation acquired by practicing a specific visuo-motor task generalizes to another task. It is generally accepted that during visuo-motor practice, an internal representation appropriate for different tasks and environments is acquainted. This notion however has been questioned by research evidence showing that adaptation to prisms during a walking task generalizes to an arm pointing or reaching task but the opposite is not true [6]. A later study indicated that a prism adaptation acquired in an arm pointing task generalized to a lower limb pointing task but a lower limb prism adaptation did not generalize to the arm [7]. This line of evidence from research in prism adaptation suggests that practicing visually guided motor behavior invokes a more general, limb-independent visuo-motor remapping, involving recalibration of higher-order brain regions in which the cerebellum has a critical role in the brain network. Alternatively, studies on visually guided aiming suggest that learning is specific to the sources of afferent information available during practice and does not generalize to other tasks [8]. Withdrawing visual feedback after practice of a manual aiming task results in a severe decrease in aiming accuracy. This decrease in accuracy is such that participants are often less accurate than controls who are beginning practice of the task without visual feedback. These opposing views about the generalization of visuo-motor practice could be due to the nature of the practiced visuo-motor tasks. Specifically, visually guided aiming does not generalize to another task whereas prism adaptation during walking can be transferred to another task. Practically, this means that practicing whole body movements with use of visual feedback results in a more generalized visuo-motor learning in contrast to practicing visual tracking of specific limb movements (i.e. aiming, eye-hand coordination).

Although the idea of practicing visually guided whole body movements has been extensively used in protocols and devices of impaired balance rehabilitation, one raising concern is the durability and transferability of practice effects. It has been shown for example that learning a novel visually-driven ankle-hip coordination may lead to improved control over certain task imposed ankle-hip relationships but can also destabilize the spontaneous, pre-existing coordination patterns [9]. In another study examining the efficacy of providing visual feedback of the centre of gravity motion during exercise [10], it was shown that this type of practice improved visual tracking performance but did not improve static balance control. Several researchers have questioned the use of learning specific visuo-motor coordination tasks through visual feedback practice because the consequences of learning do not generalize across different types of tasks, even when similar coordination solutions are involved. More evidence about the efficacy of visual feedback training in balance rehabilitation is reviewed in a subsequent section where age-related interventions are discussed.

4 Visual Stimuli and Task Parameters That Optimize Visuo-Motor Learning

The type of visual feedback cues provided during visuo-motor practice greatly influences the extent to which an internal representation of the visuo-motor task would be developed and generalized to other tasks. Specifically, continuous feedback cues allow for accurate movement production when employing on-line visual closed-loop control without access to an internal model. This type of feedback however does not allow the buildup of an internal visuo-motor transformation because continuous cues increase the dependency on feedback as closed-loop corrections permit automatic recalibration of the visuomotor mapping without access to an internal model [11]. On the other hand, an internal model of the practiced visuo-motor transformation is acquired only when feedback is provided as end-point information that is only when visual feedback about the end-point movement positions is provided.

In our laboratory, we extended and explored this hypothesis comparing the use of continuous and end-point visual cues in postural learning [12]. Specifically, we examined the impact of two types of visual cues, continuous and terminal, that were provided either as target or performance feedback information (Fig. 3). We sought to determine whether the acquisition of visually-guided postural sway can be extended to auditory driven sway and the extent to which such a transfer is dependent on the type of visual cues provided during practice. The results of this study revealed that practicing with continuous visual target cues (Fig. 3b) increase the load of on-line closed loop corrections resulting in greater accuracy at the target peak positions of the postural sway task but at the cost of increasing movement intermittency and variability. When visual feedback is continuously available, an extrinsic visuo-motor transformation can generally be mastered without the need to acquire an internal model. End-point cues on the other hand, enforce the buildup of an internal representation of the visuo-motor transformation resulting in less variable performance, improved coupling but serious target overshooting. The study concluded that the amount of visual information provided to guide voluntary postural sway has a strong influence on the relative contribution of feed forward and feedback control processes during task performance. Therefore, practicing postural tracking of periodic visual cues of repetitive nature enforces use of feed-forward control and the development of an internal model. The use of periodic visual cues in visual feedback training is critically challenged in the last section of this chapter where directions for future research and development of visual feedback tools are discussed. Another important finding of our study was that the differential adaptations acquired through visuo-motor practice did not generalize in the audio-driven postural workspace. This is because visual cues are better suited for the perception of space whereas auditory cues are more relevant for the perception of time [13]. It seems that differential practice does not impact the generalization of postural learning in the audio-motor workspace.

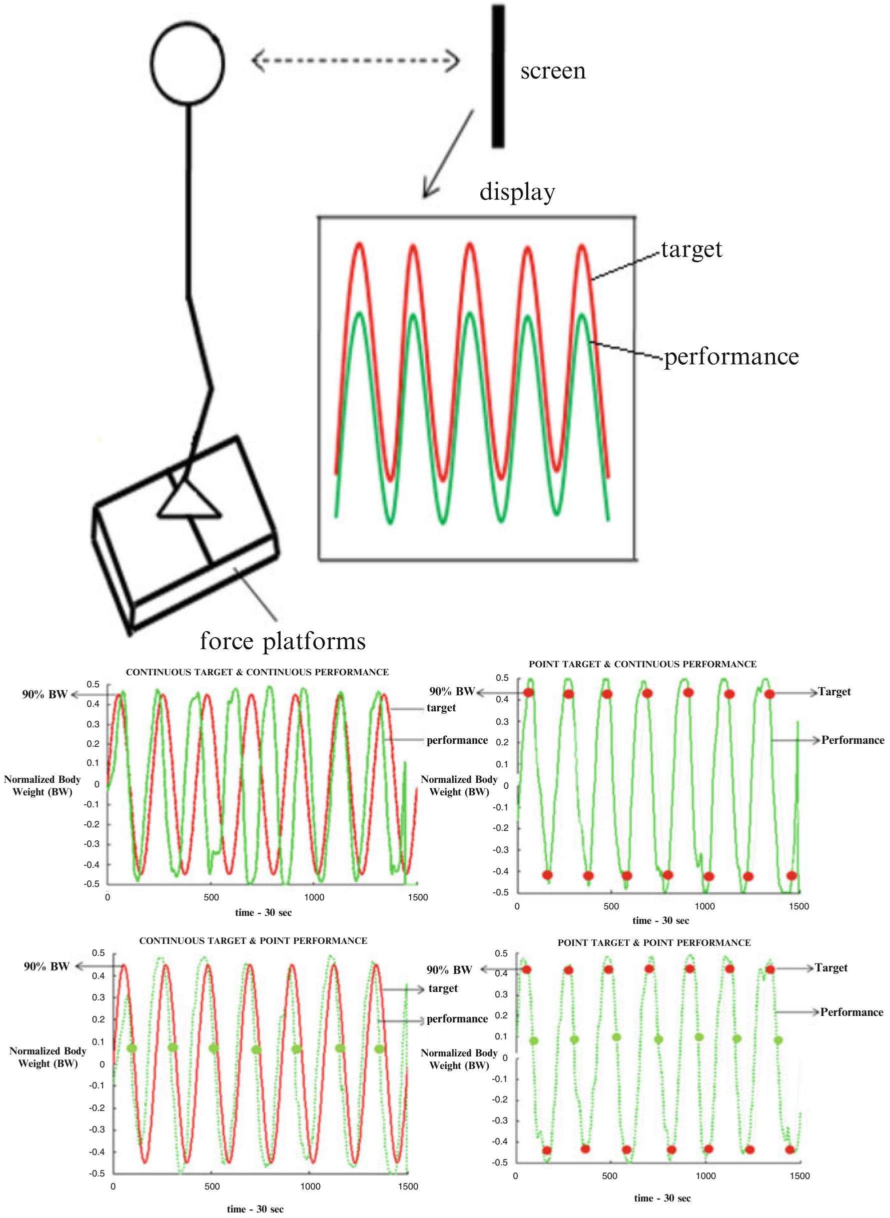


Fig. 3 (**a**) A graphical representation of the experimental protocol showing the dual force platform and the visual display (adopted from [12]). (**b**) Performance (in *green*) and target (in *red*) traces for continuous target and continuous performance feedback, continuous target and point (*dotted*) performance feedback, point target and continuous performance feedback, point target and point performance feedback (Color figure online)

Several other issues need to be considered when employing visually-driven postural learning in balance rehabilitation. Research evidence for example suggest that the color of the feedback cues may also play a role in visuo-motor adaptation and the acquisition of a novel visuo-motor transformation [14]. Moreover, the capacity to use visual feedback information to control dynamic postural sway depends on the amplitude and frequency constraints of the sway task. Specifically, a "natural" sway frequency around 0.6 Hz permits the optimal use of visual feedback information [15] whereas feedback is less effectively used by the central nervous system when sway amplitude or frequency increase.

Another important question is whether visual feedback should be provided concurrently and continuously during task performance or only at a particular time after the end of the trial. The concurrent provision of visual feedback during the trial evokes an automatic recalibration of the visuo-motor mapping which allows for more accurate performance which is lost however when feedback is not available any longer [16]. Individuals therefore may become so reliant on visual feedback that their performance seriously deteriorates in the absence of it. Post trial feedback on the other hand allows for the buildup of a "cognitive strategy" or internal model that can be optimally used to perform without feedback or to adapt to a novel environment.

The additional value of providing feedback information about sway when individuals already use visual target information to control their posture is also arguable [17]. Individuals using visual target information were no better in controlling their leaning posture when CoP feedback was provided in addition to visual target information. This is because performance feedback is usually contaminated with more stochastic variability in the signal whereas performers prefer to rely on less variable and simpler structure information.

In summary, there are several stimuli properties and task parameters that can influence visuo-motor learning in visual feedback training systems. There is no doubt that more research along these lines is required to unravel the important mechanisms underlying visuo-motor learning. Moreover, a critical issue that is addressed in the following sections is whether and how visuo-motor learning is constrained by aging. This is important particularly when considering that the target end user group of visual feedback technology is the aging population and particularly those older adults with balance impairments.

5 How Aging Affects the Ability to Learn Novel Visuo-Motor Tasks

With increasing age, individuals prioritize the use of vision and rely heavily on visual inputs for controlling their posture since somatosensory inputs become less reliable due to peripheral neuromuscular degeneration [38]. Nevertheless, the ability to use visual feedback information for controlling static or dynamic balance also diminishes with age. Age-induced delays in the sampling and processing of visual information required for the on-line control of posture and locomotion might be a contributing factor to impaired balance function and associated increased incidence of falling [18]. These are reported in precision stepping [19] and obstacle avoidance [20] during locomotion and have been attributed to neural degeneration of the visual and visuo-motor pathways in the brain. In a study investigating the use of visual feedback about CoP position to control static postural sway, only young participants were able to decrease the amplitude and increase the frequency of their sway based on visual feedback information [21]. Moreover, removal of the visual feedback resulted in a 'destabilizing' of standing in elderly adults whereas young individuals were able to maintain the speed and precision of dynamic sway when visual feedback was withdrawn.

In our laboratory we have investigated the capacity of older women (>65 years of age) to learn a novel visuo-postural coordination task [22]. Elderly women stood on a dual force platform and were asked to shift their body weight between the two platforms while keeping the vertical force produced by each foot within a ±30% force boundary that was visually specified by a target sine-wave signal (Fig. 4a, white circles inside the target sine curve indicate the % of bodyweight applied by each foot). Practice consisted of three blocks of five trials performed in 1 day followed by a block of five trials performed 24 h later. Older women made longer weight-shifting cycles and had lower response gain and higher within-trial variability compared to younger women suggesting a weaker coupling between the visual stimulus and the response force (Fig. 4b). Regardless of age however, visuo-postural coupling improved with practice suggesting that learning of the particular visuo-motor coordination task was apparent in both groups. Older women however employed a different functional coordination solution in order to learn the task that was imposed by age-specific constraints in the physiological systems supporting postural control.

In summary, with aging humans rely more heavily on visual information for controlling their balance despite the age induced delays in the sampling and processing of visual information for the online control of posture and locomotion. Visuo-motor processing delays however might be compensated by reinforcing the natural process of sensory substitution with the provision of augmented visual feedback.

6 Improving Balance Control in Aging Using Visual Feedback Training

Based on the idea that older people maintain their ability to learn novel visuo-motor transformations, visual feedback protocols and devices have been developed promising to improve control of balance and locomotion and prevent falling due to age degeneration or a specific pathology. Visually guided postural training with

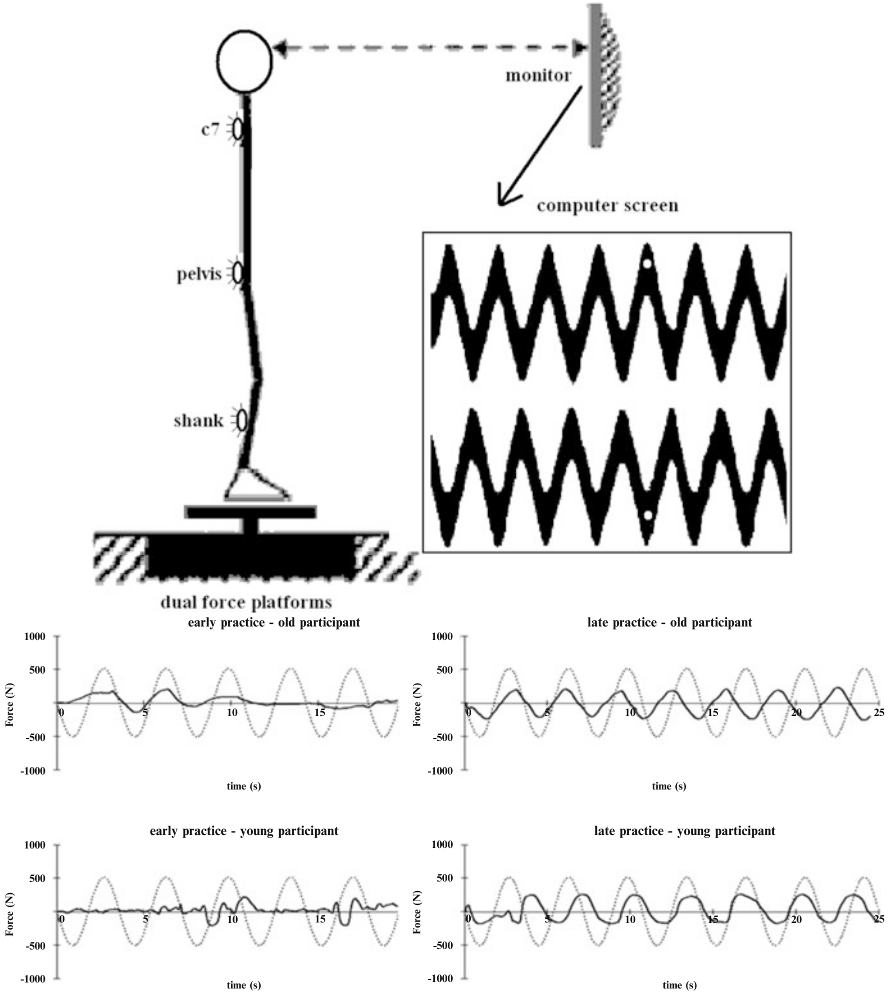
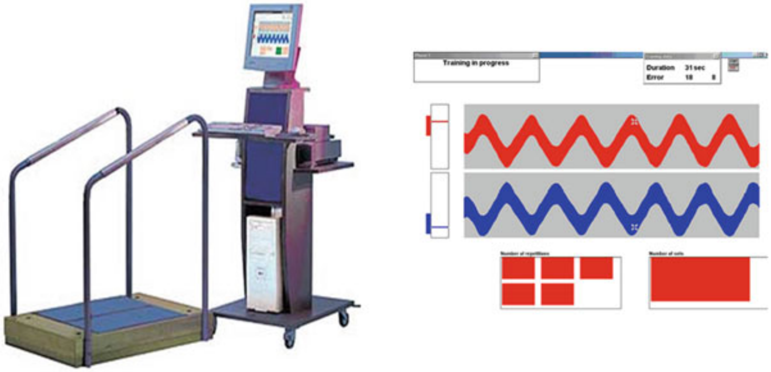


Fig. 4 (**a**) Schematic representation of the visual feedback task used by Hatzitaki and Konstadakos [22]. The subject stands on a dual force platform and is asked to shift body weight between the two platforms while keeping the vertical force produced by each foot within a ±30 % force boundary that was visually specified by a target sine-wave signal (*white circles* inside the target sine curve indicate the % of bodyweight applied by each foot). (**b**) Time series of the ground reaction force (*solid line*) produced during one weight shifting trial superimposed on the stimulus force (*dotted line*) for an old (*top*) and young (*bottom*) participant during early (1st trial, *left panel*) and late (15th trial, *right panel*) practice. Target force is scaled to individual body weight

the use of enhanced visual feedback has provided alternative means of improving balance function in healthy community-dwelling older adults, frail elderly living in residential homes and hemiparetic stroke patients. This is because practicing visually guided postural sway enhances the sensory-motor integration process through a recalibration of the sensory systems contributing to postural control [23]. Computerized biofeedback training that focuses on manipulating individual, task, and environmental constraints concurrently can significantly improve dynamic postural control and sensory integration in older adults with a previous history of falls [24]. An 8-week computerized training program with a feedback fading protocol improved reaction time in the dual-task posture paradigm which suggests that this type of training improves the automaticity of postural control [25]. Similarly a 4-week balance training program with the use of visual feedback improved the functional balance performance of frail elderly women [26]. The provision of augmented visual feedback during balance training can improve stance symmetry and postural sway control in stroke patients as well [4]. The effectiveness of center of pressure biofeedback in reestablishing stance symmetry and stability was compared to conventional physical therapy practices in hemiplegic patients. Postural sway biofeedback was more effective than conventional physical therapy practices in reducing mean lateral displacement of sway and increased loading of the affected leg.

In a series of studies performed in our laboratory we have investigated the use of visual feedback training as a tool for improving static and dynamic balance in the population of healthy elderly women. We used a commercially available visual feedback device (ERBE Balance System, Elektromedizin Gmbh, Fig. 5) that consists of a dual force platform recording the vertical ground reaction force under each foot (sampling rate: 100 Hz) while on-line visual feedback about each force vector is provided by a cursor (i.e. asterisk) displayed on a computer screen located


Training in progress

Duration 31 sec
Error 18 8

Fig. 5 A commercially available biofeedback device consisting of a dual force platform recording the vertical ground reaction force under each foot while on-line visual feedback about each force vector is provided by a cursor (i.e. *asterisk*) displayed on a computer screen located in front of the subject in front of the subject (1.5 m ahead, eye-level). The training task requires shifting body weight between the right and left foot (for Medio-Lateral, M/L training) or from toes to heel (for Anterior–Posterior, A/P training), while maintaining each platform's force vector within a visually specified sine waveform constraints. The bandwidth of each sine waveform curve can be individually adjusted to ± % of bodyweight. The duration of the training trial is specified by the number of required weight shifting cycles. Each time either force vector exceeds the ± % limit in either direction, the movement of the cursor on the screen stops and a spatial error is recorded. Our participants practiced with this type of visual feedback for 4 weeks (3 hourly sessions per week). Visual feedback training improved static postural control only in the group practicing in the A/P direction whereas no adaptations were observed in the group practicing sway in the M/L direction [27]. In addition, the same visually guided training increased the limits of stability and enhanced the use of the ankle strategy for maintaining balance during leaning and dynamic swaying tasks [28]. More importantly, practicing visually guided weight shifting in the M/L direction improved the postural adjustments associated with a moving object avoidance task [29]. Specifically, as a result of practice, postural response onset shifted closer to the time of collision with the obstacle and sway amplitude during the avoidance decreased substantially. These observations suggest that visually guided practice enhances older adults' ability for on-line visuo-motor processing when avoiding collision eliminating reliance on anticipatory-predictive mechanisms. Contrary to static balance improvements that were apparent in the group practicing in the A/P direction adaptations in obstacle avoidance skill were more evident to the group practicing in the M/L direction. These findings suggest that specifying the direction of visually guided sway seems to be critical for optimizing the transfer of training adaptations.

In conclusion, the impact of visual feedback training on balance performance is an issue surrounded by continuing controversy. On one hand, training-induced improvements of both static [27] and dynamic [29] balance have been reported in healthy and frail older adults [26]. On the other, several investigations have failed to reveal long-term benefits on static and/or dynamic balance [30, 31] although acute improvements of weight bearing symmetry are reported in stroke patients. More importantly, the observed improvements, noted only in those dynamic balance tasks that are specific to the training, give rise to the possibility of motor learning effects. Controversies between different study results may be attributed to the diversity of tasks employed in visual feedback training that vary in several directions (anterior, posterior, lateral, diagonal), movement forms (weight shifting, leaning, stepping), stance positions and support surfaces configurations as well as in the type of target and performance cues used in the visual representations. It appears that the benefits of visual feedback training are mainly limited to those tasks that are specific to the training. This could be due to the direct link between visual information and specific motor response loci developed through visually guided actions that does not permit the generalization between vision and action found in one posture to other postures [32]. Thus, task specificity during training could be implicated for the absence of training effects on functional measures of static and dynamic balance performance.

Transfer of skill learning is therefore an important issue that needs to be addressed when considering the efficacy of visual feedback training for improving balance function.

7 Future Research and Technology Development Directions

The regularity of visual target motions used in visual feedback training enhances the use of predictive mechanisms in motor learning [3]. The problem though with practicing of stereotypic and highly predictable visual cues is that this type of visual feedback training does not enable the visuo-motor system to use its online sensory-motor calibration and perception-action processes. As a result, practice leads to the development of an internal motor plan of a particular visuo-motor task that does not generalize to other types of tasks. This lack of generalization seriously limits the number of functional coordination solutions the motor system uses in order to adapt to a novel task or environmental condition.

A quite promising solution to the problem of task specificity is to introduce a more variable approach in the presentation of visual cues adopting target cues that are non periodic and therefore less predictable. The problem though with using more variable and less predictable visual cues in visuo-motor practice is that the human central nervous system perceives the stationary, low frequency visual target cues whereas it is less reliant on the performance feedback signal that has higher frequency and less stationary properties. Nevertheless, recent pilot research evidence from our laboratory suggest that adults can couple their sway and visual (gaze) motions much better to a chaotic (i.e. Lorenz attractor) visual target motion (Fig. 6a) than a periodic target motion (Fig. 6b) [39]. Although this is a surprising finding it may be explained based on the fact that the evolution of healthy movement variability can be described in terms of deterministic processes as well as being complex [33]. It is this optimal combination of determinism and complexity that enables us to adapt in our environment in a stable but flexible manner. Optimal movement variability degrades with aging and pathology (e.g. Parkinson’s Disease) and has also been associated with a risk of falling. Since the goal of balance rehabilitation is to restore optimal sway variability i.e. the balance between regularity and complexity, we believe that the use of more variable and less predictable visual cues to guide postural sway practice holds the potential of optimizing the effects of visual feedback training. More research is required however for indentifying the stimuli parameters that will optimize the learning process.

A relatively recent development of visual feedback based systems is **exergaming**. Exergaming refers to technologically advanced virtual reality systems which combine exercise with video games. These systems offer an attractive and motivating balance training tool that has been widely used in community dwelling older adults [34, 35]. A computer game-play system that employs user interface visual feedback loops, so as to physically but also mentally involve the user. Researchers and practitioners in the field of aging have introduced elderly audiences to cognitive training and stimulation games which are now enjoyed within the context of computer and/or game consoles. Numerous recent studies have investigated how exergaming can be specifically applied to the needs of seniors. The most common platform used for balance training is the “Nintendo Wii”. Most studies that have tested exergaming as a balance training tool in healthy elderly report positive results with respect to improvements in balance ability after a training period, at least as much as the conventional/traditional exercise. The greater attainment of exergames, is the greater extend, to witch, individuals, seem to enjoy the exercise by interacting in a virtual reality environment. The use of virtual reality in balance rehabilitation

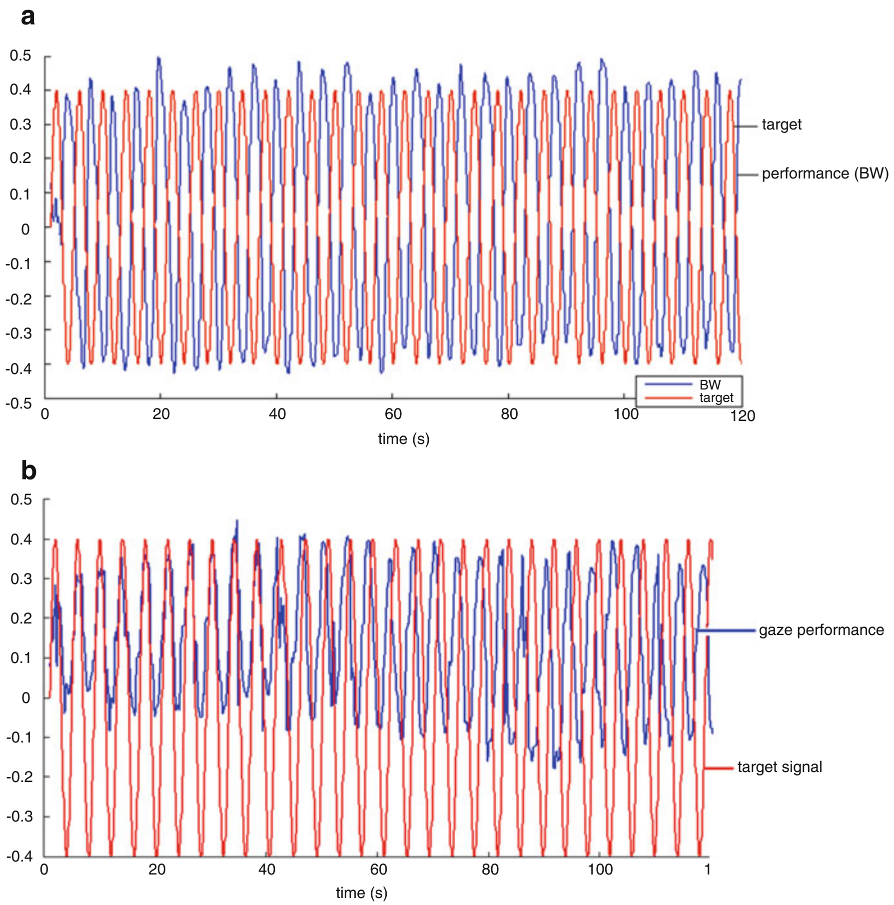


Fig. 6 Examples of performance (*blue line*)–target (*red line*) curves during postural tracking of different complexity stimuli motions: (**a**) Body Weight (BW)–target (sine), (**b**) gaze–target (sine), (**c**) Body Weight (BW)–target (Lorenz attractor) and (**d**) gaze–target (Lorenz attractor). Data published in [39] (Color figure online)

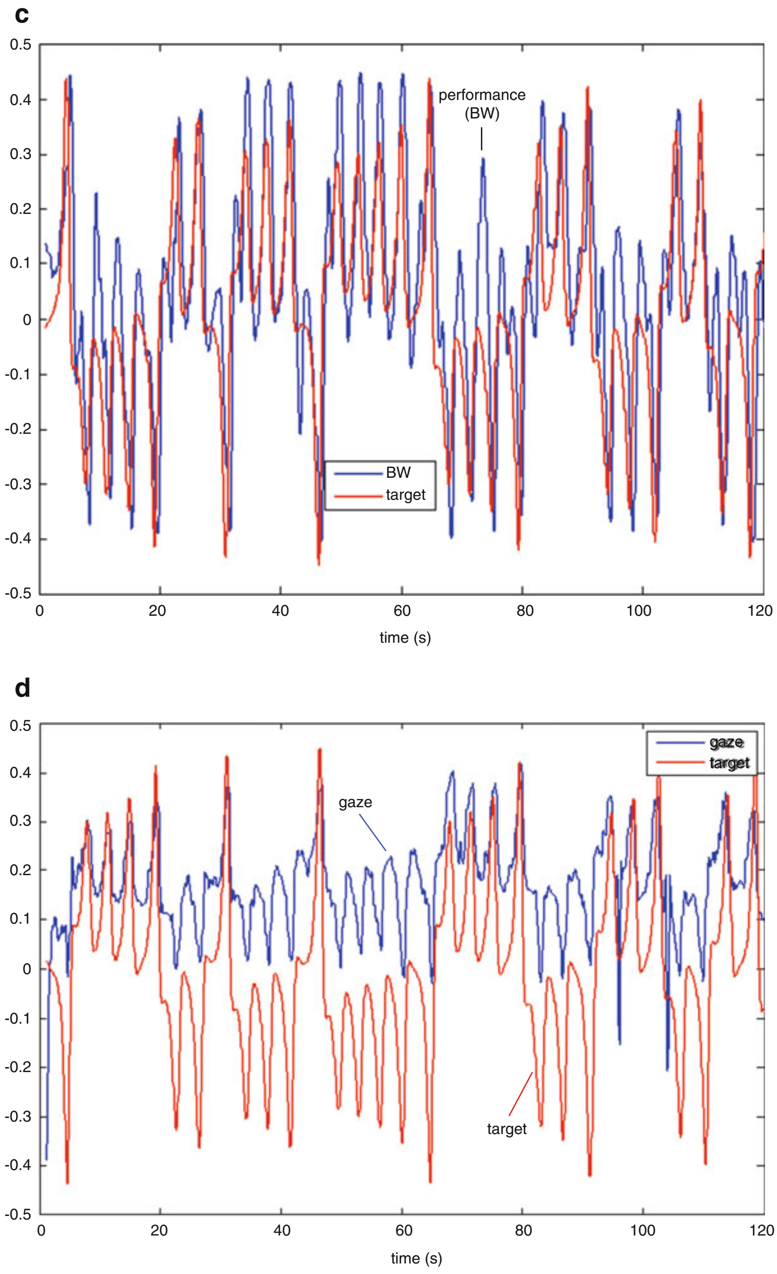


Fig. 6 (continued)

has the potential to offer experiences which are engaging and rewarding and more importantly simulate real life balance challenging conditions [36]. This line of research is certainly still growing and has been the subject of recent systematic review [37].

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