

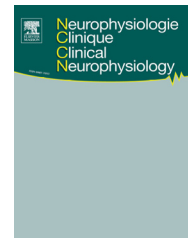


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REVIEW/MISE AU POINT

Posture and cognition in the elderly: Interaction and contribution to the rehabilitation strategies



*Posture et cognition chez le sujet âgé : interaction et
contribution aux stratégies de réhabilitation*

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Summary In this paper we review the effects of aging on sensory systems and their impact on posture, balance and gait. We also address cognitive aging and attempt to specify which altered cognitive functions negatively impact balance and walking. The role of cognition in postural control is tested with dual-task experiments. This situation results in deleterious effects due to an attentional overload. Given the human cognitive system has limited capacities, we propose that simultaneously performing two tasks depends on the capacity of each individual to perform these tasks on a continuum between automatic execution to highly controlled performance. A level of maximum control exceeds the subject's attentional capacity, which makes it impossible to perform both tasks simultaneously. The subject therefore prioritizes one of the tasks. We use representative dual-task studies from the literature to illustrate the relationship between the different cognitive components and their impact on the control of posture and gait in elderly subjects with altered cognitive capacities and with elderly subjects who are fallers or who have altered sensory-motor capacities. Recently this postural-cognitive relationship was addressed with a new approach. We report how cognitive training can improve dual-task management and we attempt to define the cognitive mechanisms that may be responsible for better postural balance.

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Résumé Dans cet article, nous passons en revue les effets du vieillissement sur les systèmes sensoriels et leurs conséquences sur les performances de posture, d'équilibration et de marche. Nous abordons également le vieillissement cognitif et tentons de préciser,

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parmi les fonctions cognitives altérées, celles qui peuvent participer à la détérioration de l'équilibre et de la marche. L'implication cognitive dans le contrôle postural est traitée par l'approche expérimentale des double-tâches posturo-cognitives. Cette situation présente un effet délétère du fait du surcoût attentionnel. Le système cognitif humain ayant des capacités limitées, nous proposons que la réalisation simultanée de deux tâches dépend de la capacité de chaque sujet de réaliser ces tâches selon un continuum compris entre une réalisation automatique jusqu'à une réalisation hautement contrôlée. Un niveau de contrôle maximal dépasse les capacités attentionnelles du sujet rendant la réalisation simultanée de ces deux tâches impossibles. Le sujet priorise alors une des deux tâches. Parmi la vaste littérature sur les double-tâches, nous décrivons ici des travaux représentatifs des relations entre différentes composantes cognitives et leurs conséquences sur le contrôle de la posture et de la marche, au cours du vieillissement, chez des sujets chuteurs ou dont les capacités sensorimotrices sont altérées, et chez des personnes dont les capacités cognitives sont altérées. Récemment, cette relation posture-cognition a été envisagée de façon nouvelle. Nous décrivons ici comment un entraînement cognitif est capable de favoriser une meilleure gestion de la double-tâche et tentons de préciser les mécanismes cognitifs qui seraient responsables d'un meilleur équilibre postural.

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Effects of aging on the sensory systems and posture, balance and gait

Age-related changes to the sensory systems

Maintaining balance and preserving the rhythm and stability needed for walking requires a complex system of control that is able to adapt to internal and external changes. This system of control depends on the cooperation between sensory systems, which are able to detect the position and movement of the body and the visual environment, and effectors, which create appropriate postural and kinetic reactions. The vestibular system, which detects the movement of the head, provides information on the changes of the orientation of the body in space and movement. The vestibular system uses compensatory reflexes that play a major role in maintaining balance. The afferent visual sensory system makes it possible to integrate the information relative to objects in the environment. Vision also makes it possible to gather information on movement of the subject in relation to the environment. Proprioceptive and tactile information (muscle spindles, Golgi tendon organs) provide information on the position of the body and the different parts of the body in relation to each other and to the surrounding space. Each sensory input has its own domain of action. In this way, visual and proprioceptive modalities have a threshold for stimulation that is low enough to perceive slow movements and oscillations while standing. Conversely, the vestibular system has a primary role in the detection of rapid movements due to its anatomy and physiology. These sensory modalities are complementary and have partly overlapping functions. The complementary information that is a result of the overlapping functions makes it possible to improve perception and the coding of movements. The integration of this sensory information participates in the elaboration of an internal model of the representation of orientation and movement. This multisensory integration helps generate appropriate motor responses adapted to situational constraints (especially environmental constraints such as obstacles and light...) (e.g. [49,63]).

Aging is associated with many physiological changes of the different sensory systems (Table 1). The main changes that affect the vestibular system affect the hair cells in the semicircular canals, the maculae of the saccule and the utricle, the primary and secondary vestibular neurons, as well as the central vestibular structures [14,43]. Modifications of the visual system consist of a reduced sensitivity to contrasts, a disruption in the perception of depth (which is particularly important when confronting obstacles), and a deterioration of dynamic visual acuity when the subject or target moves [59]. The somatosensory system creates points of reference that are important for balance. Tactile information from feet and their contact with the ground can deteriorate. In the same way, the capacity to detect position and direction of the joints movements is reduced [80,92]. In the motor system, the most significant effect of age concerns the changing characteristics of muscles: reduced muscle strength tied to both the muscular fibers that are decreased in number and size, and the changes in the central motor commands [28,74]. Reaction time increases and the muscle contraction speed decreases. All of this can prevent elderly subjects from using adequate force and reacting quickly to postural disturbances [14].

Age-related changes in posture, balance and gait

In general, posture and balance have been compared in different conditions with static or dynamic tests and during walking in young adults, middle-age adults or older non-fallers (with optimal physiological capacities), and populations at risk of falling (having fallen at least once in the previous months).

Changes in the posture (orientation of the body in relation to vertical gravity) have been identified as one of the main factors that contribute to falling in elderly populations [90]. With age, the subjective postural vertical becomes less precise, especially for very old subjects. A postural vertical that is tilted backwards has been proposed as an explanation for retropulsion that is often observed in elderly subjects

Table 1 Main sensory and perceptive changes related to age and main consequences on the control of posture, balance and gait.

Sensory system	Impact on sensorimotor system and perception	Impact on posture, balance and gait
Vestibular	<ul style="list-style-type: none"> ↓ Hair cells in the sensory epithelia ↓ Number of otoconia ↑ Otoconial fragments ↓ Primary vestibular neurons and cell bodies (Scarpa's ganglion) ↓ Number of vestibular neurons (vestibular nuclei) Poor perception of vertical Dizziness Oscillopsia Disturbed perception of head orientation Disturbed perception of body movement (spatial navigation) 	<ul style="list-style-type: none"> Postural deviation in relation to the vertical Postural instability Enlarged support surface ↓ Head and trunk stability ↑ Center of pressure oscillations ↑ Energy necessary for stability Unstable walking ↓ Walking speed, stride length ↑ Stride frequency Deficit in gaze stabilization ↓ Gain of vestibulo-ocular reflex ↑ Latency of ocular movements ↑ Threshold of oculomotor responses Note: Changes related to age can mimic a bilateral reduction of vestibular function
Visual	<ul style="list-style-type: none"> ↓ Visual acuity ↓ Depth perception ↓ Sensitivity to contrast ↓ Accommodation Narrowing of the visual field ↓ Adaptation to darkness ↓ Dynamic visual acuity (during movements of the environment or of the subject) ↓ Adaptation to moving visual stimuli Difficulties in perception of objects in the environment Disturbed perception of movement of the environment 	<ul style="list-style-type: none"> Postural deviation in relation to the vertical Postural instability Instability while walking Difficulties negotiating obstacles (depth perception) Disruption of gaze stabilization (saccade, smooth pursuit, optokinetic reflex) Note: With age there is an increased dependence on visual information to maintain balance (dangerous especially in cases of a moving visual environment)
Somatic sensation	<ul style="list-style-type: none"> Impaired proprioceptive cues (muscle spindles and Golgi tendon organs) Altered spindle responses to passive and active lengthening Altered tendon organ responses Loss of intrafusal fibers and motoneurons ↓ Proprioceptive sense of neck muscles Difficulty to detect head orientation (important to obtain a stable platform for visual and vestibular receptors) ↓ Sense of position and movement ↓ Capacity to detect the position and direction of joints Deterioration of tactile information from feet Decreased perception of contact with the ground 	<ul style="list-style-type: none"> Postural deviation in relation to the vertical ↑ Local instability ↓ Postural stability, especially on foam ↑ Gait variability Note: The consequences of a reduced proprioceptive acuity can be especially substantial as neck receptors are known for their role in the substitution of missing vestibular information (for young subjects)

who have fallen. These changes in posture could be related to a less robust internal model of verticality [13].

Postural performance of the elderly is generally studied by examining the characteristics related to maintaining balance while standing quietly [64,95,108]. Data from the literature indicate that despite a possible alteration of the sensory systems or effector systems, maintaining balance in the least demanding of conditions is not necessarily modified for robust elderly subjects. There is no difference in postural performance between non-fallers and young or middle-age subjects [17]. However, performances in this situation could not predict performance after sudden postural disturbances [62]. After a sudden disturbance to balance, the central nervous system must plan the necessary postural corrections to maintain dynamic stability. Compared to young adults, older

adults have more difficulty regaining their balance [96]. Elderly subject who demonstrate weaker scores for clinical measures of balance have diminished postural performance and higher muscular response as compared to elderly subjects with optimal physiological capacities [53].

These changes in postural correction related to age can be tied to physiological changes of different sensory systems that participate in the control of posture, balance, and gait. The consequences of these changes are detailed in Table 1. Damage to the inner ear that leads to instability is not specific to elderly populations; however, the consequences can be more severe for elderly subjects [45]. These changes disturb vestibulo-spinal and vestibulo-ocular functions responsible for balance capacities and gaze stabilization [46,73,105]. Visual motion stimuli lead to greater

postural oscillations than in populations of young subjects [22] and adaptation to the stimuli requires more time [72]. The capacity to judge depth is also particularly important in difficult walking environments with obstacles [65]. Disturbances in posture and balance can also result from the loss of proprioceptive acuity [26,39]. Difficulties finding balance can also be the consequence of physiological changes related to the motor system, such as a reduction in muscle strength [31], tendon stiffness [44], or the slowing of muscle contraction velocity [41]. Specifically, reduced muscle strength has been cited as a risk factor for falling [40]. However, a longitudinal study conducted over a period of nine years (71.1 ± 5.4 years, $n = 12$) showed that despite an overall change in muscle size and strength, contractile function of muscular fibers is preserved with age [30]. These data suggest that existing muscle fibers can compensate and partially correct the deficits of muscle mass in order to maintain an optimal capacity of strength production, even in very old subjects (80 ± 5.3 years at the end of the study). Clinically speaking these results demonstrate the importance of rehabilitation programs that focus on dynamic stability control exercises for physical therapy or for fall prevention strategies [5].

With age, walking characteristics change. In general, the elderly walk slower than younger people [19]. A reduced walking speed is the result of shorter strides length [60] and increase in double-support duration [29], whereas the stride frequency increases. The elderly demonstrate an increased variability in foot placement and elevation [15,51,113] during walking as compared to younger adults. Many factors may be responsible for this variability such as weakness of ankle dorsiflexors and plantarflexors. This weakness could damage the stability control and could potentially lead to falls [52]. With age there is greater postural sway in anteroposterior and mediolateral directions [53] and the acceleration of the head and pelvis are reduced during walking [66]. For the elderly with optimal physiological capacities, adopting a reduced speed and a shorter stride has been interpreted as a sign of a less destabilizing gait [109]. This suggests that the elderly compensate for their reduced physical capacities by being more careful and by reducing their energy used in movement [12,86]. Increasing the duration of the preparation phase of the movement is also a modification that minimizes postural disturbance created by movement [67]. Contradictory interpretations have been reported by other studies that indicate that changing walking parameters can be a risk factor for falling [33]. Subjects who have fallen in the previous year require more time for anticipatory postural adjustment. Negotiating an obstacle can be a risk factor. Disturbed anticipatory postural adjustments could come from an "insufficient central processing capacity for motor planning and gait regulation" [100]. Many studies, have found that walking speed is a reliable marker for changes in mobility. Speed tends to reduce with age and following chronic diseases. Based on these results, it has been suggested that reducing walking speed is a gauge of the effects of biological aging on the health and functional state. A challenge for future studies will be to identify the mechanisms behind these changes in posture and gait and to specify their prognostic value [86]. Symptoms of instability and deficits in maintaining balance can be worsened by pathologies that are frequently present

in elderly populations, such as: Parkinson's disease, peripheral neuropathy, arthritis, and sarcopenia. Sensory damage such as benign paroxysmal positional vertigo, cataracts, and impaired sense of position are also associated with instability. Often one or more pathologies are responsible for symptoms of instability for the elderly [14]. In general, these pathologies increase postural sway, the range of postural adjustments and the gait variability. The presence of multiple risk factors increases the risk of falling [97].

Alterations of sensory and motor functions and of their central processing are not the only causes of age-related balance impairment. Cognitive aging is also an important factor. Some cognitive functions are sensitive to aging [2,76,83]. In the following paragraphs we address the subject of cognitive aging attempting to specify which altered cognitive functions participate in posture control, balance and gait.

Effects of aging on cognition

Age-related cognitive changes vary within and among individuals, which can be explained by different levels of cognitive resources that are often related to socio-cultural factors and each individual's personal history. The onset and the severity of cognitive decline for an individual varies according to the functions considered, but also within a single function according to the mechanisms or systems involved.

There are two main approaches to cognitive aging: a global approach and an analytical approach. The *global approach* aims to describe the general factor or factors that make it possible to explain the cognitive deficiencies in the elderly. This approach is founded on the idea that the human cognitive system has limited capacities and that the elderly have a deficit of cognitive resources. In this respect, for example, the capacity of working memory will determine the feasibility and the quality of the information processed. In the same way, the management of the processed information, meaning their activation and inhibition, will be very important in order to accomplish a task. The success or failure on a test will depend on the speed with which this information is processed. Studies conducted with a global perspective attempt to describe how the limits of the processing system of the elderly (attention, capacities of working memory, mechanisms of inhibition, and speed of processing) limit functioning. The *analytical approach* makes it possible to consider complementary factors that are different from those assessed in the global approach. For the analytical approach, the differences in age-related performance are explained by the sensitivity to age of each of the processing components that are implicated in a certain task. The components correspond to structural or functional units. Research with this approach aims to identify the interactions between the different components implicated in a task in order to understand how one malfunctioning component affects the others. This approach is complemented with a *multifactorial approach* that considers the performance of elderly subjects as the result of the interaction between different components of processing. These three approaches are complementary and it is necessary to keep this complementary nature in mind when researching a model to

explain cognitive dysfunction. We will focus on the functions and mechanisms that may have an impact on regulating posture and gait and the rehabilitation of these functions and mechanisms.

Attention

Attention is involved in all intellectual and behavioral performance encountered in daily life. It is now common to include attention in the category of executive function as it has a function of control. Attention is necessary for the decision making process, in which individuals develop an action that is appropriate for the given situation. This decision is the result of an analysis, a process of reflection, and a strategy. There have been multiple models of attention proposed in the last twenty years. All insist on these notions of control and acknowledge, for most of them, the existence of an attention system. The models differ in the definition of different components or sub-systems or differ in the dynamics of attention components in information processing.

One of the difficulties encountered when studying the effects of aging on attention faculties is to differentiate between attention impairment and a general slowing of the processing of information that affects every step of processing, from the most peripheral to the most central. Even though it is sometimes difficult to determine if certain components of attention are disturbed for elderly subjects or if the experiment results are the results of a general slowing of information processing, certain attention components appear to be sensitive to the effects of aging [34].

Selective attention is reported to be less effective in elderly subjects compared to young subjects [75]. Selective attention makes it possible to select information to process and the type of response as it is impossible to process all information that we are presented with. The notions of capacity, filtering and control are involved in this process. Only a small amount of information is filtered and processed in order to avoid overloading the mental system. Selective attention consists both of the activation of a process of centralization of the object of attention (focus of attention) and of the active inhibition of distracting elements that can potentially disturb and interfere with this focus. The selected information must be maintained at a high level of processing for a prolonged amount of time in order to make a clear and precise representation, and to trigger an appropriate action strategy. In this respect, attention is strongly tied to working memory, conceptually and anatomically, which has been highlighted by many studies. The idea of distractibility (the difficulty to maintain attentional focus) and the idea of flexibility (capacity to constantly displace and reorient the focus of one's attention) must be taken into consideration. Flexibility is an essential executive mechanism that intervenes in all complex situations. It makes it possible to reorient the contents of thoughts and actions in order to be able to perceive, process, and react to situations in different ways. Some authors suggest that aging is associated with a deficit of the disengagement component of selective attention [32] and a deficit in the *process of inhibition* [27,35]. In working memory, these

processes control the access, maintenance and rejection of non-pertinent information for the task at hand.

The data from *divided attention* associated with aging are contradictory. Divided attention directs one's attention towards two sources simultaneously. As the quantity of available attentional resources are limited it is not possible to effectively perform two tasks at the same time beyond a certain level of complexity. The dual-task paradigm is widely used to study how attention is shared. This paradigm consists of completing two tasks simultaneously. There are many explanations for the age-related difference observed in dual-tasking. First, dual-tasking is relatively complex as it combines not only the complexity of single tasks but also the coordination of two tasks which involves additional cognitive or attentional energy. Secondly, everyone has a limited amount of resources available to perform two tasks and elderly subjects have less attentional resources than younger adults and are, therefore, more sensitive to dual-task situations. Thirdly, dual-tasks use conscious or controlled attentional processes and we know that the effects of cognitive aging are more marked for these processes than they are for automatic processes. The ideas of *automatic processing* and *controlled processing* proposed by Schneider and Shiffrin [85] are important for this concept. The intake of certain information or activities can happen outside the limits of attentional control. All activities that are over-learned will occur automatically using minimum attentional resources or in absence of all conscious attentional control. Thus, if a subject is asked to perform two tasks that do not require attention (pre-attentional level) and that can be performed automatically, a large amount of information can be processed. On the other hand, if both tasks require attention, and are thus performed with a control mode, a limited amount of information can be processed and performance is lower than if the subject performs each task separately. And fourthly, performance on dual-tasks is often tied to executive function especially to a central executive system as defined by Baddeley [9]. It is important to highlight that a number of studies have found no age-specific effects for dual-tasking [84]. This appears to be related to the nature and/or complexity of the tasks used as well as the way that the cognitive cost of the dual-task is evaluated (see [103] for a meta-analysis).

Memory

Some memory systems are more sensitive to the effects of aging than others. We will primarily address *the working memory*, which is a cognitive system that is highly sensitive to the effects of aging. It is central in cognitive research because it challenges executive abilities in many areas such as reasoning, learning, and comprehension. Baddeley [8] describes working memory as "...a temporary storage system under attentional control that underpins our capacity for complex thought". This memory makes it possible to temporarily manipulate and store information during thinking and reasoning tasks. These memory processes are used during day-to-day familiar activities, or during more demanding tasks that require greater effort and new thinking. One way of understanding working memory is

to consider the types of memory we need when we read, follow the news headlines, plan future activities, or perform several tasks simultaneously. As we have seen previously with attention, one of the important concepts of working memory is that it is under attentional control, indicating that we choose where to direct our attention. Working memory is limited in capacity, which means that we cannot store and manipulate endless amounts of information. Therefore, the types of tasks we can undertake will be constrained by working memory resources. Working memory also limits, to some degree, the types of information we can handle concurrently. While there are some types of tasks that can be carried out at the same time, other types of tasks compete for the same resources within the working memory system and, therefore, interfere with each other.

The original working memory model [7] consists of three components. The most important component is a system for controlling attention, known as the “central executive”. This is used to ensure that working memory resources are directed and used appropriately to achieve the goals that have been set. It is responsible for the control and allocation of attention. There are also two temporary storage systems: the “phonological loop” and the “visuospatial sketchpad”. These two storage mechanisms are regarded as “slave subsystems”, the real “brain” of the working memory system being the central executive. In 2000, Baddeley added a fourth component to the working memory model; the “episodic buffer” [6]. This new component allows a link to long-term memory, a way of integrating information from all of the other systems into a unified experience. The core role of the central executive is to allocate attention within the working memory system, and this is done via *focusing*, *dividing* and *switching* attention. It provides the higher levels of executive control that are required for carrying out new behavior requiring new approaches. Therefore, the central executive coordinates concurrent activities, inhibits, updates and redirects the action of many skills, that are sensitive to the effects of aging. It is increasingly helpful to view the central executive of working memory as a broad attentional control space. This type of system closely resembles what many authors refer to as executive function. If we take a current definition of executive function, i.e. processes that control and regulate thought and action, it becomes clear that the concepts of “central executive” and “executive function” are very similar.

Executive functions

Executive functions represent a set of mental processes. Pennington and Ozonoff [77] have suggested that executive functioning can be divided into six sub-skills: (1) planning and problem solving, which is a type of skill that refers to the preparation of future actions to achieve goals and the generation of solutions to address difficult situations; (2) set shifting, which refers to the ability to change response/strategies when necessary, or after feedback indicates that the original plan is not working; (3) fluency which refers to the ability to quickly and efficiently search for and generate new information; (4) inhibition (see above); (5) working memory (see above); and (6) self-monitoring which

is the ability to check on progress towards goals. However, while we can divide executive functioning into a number of distinct sub-skills, these skills are still loosely related to each other [68].

The effects of aging on these executive functions requires a complex analysis as it depends on many of the aforementioned factors that are primarily related to the manipulation and analysis of complex elements of the task. If we focus on the working memory tasks, and specifically on dual-tasks, which is important for the interaction between cognition and posture or gait, we can refer to the “cognitive saturation” hypothesis which states that the decline in dual-task performances will be more important in elderly.

Posture-cognition interactions in the elderly

In the literature on posture control and gait, dual-tasking most often consists of simultaneously performing a postural task (primary) and a cognitive task (secondary). Each of these tasks is on a scale that goes from automatic task performance to a highly controlled performance. For two tasks that are sufficiently simple to be performed automatically, little or no attentional resources are required. In this case, each task will be performed optimally (e.g. sitting and fixating a stationary target). On the other extreme, if both tasks are difficult enough to require a full control, the attentional capacities of the subject will be overloaded and it will not be possible to simultaneously perform both tasks. The subject will prioritize one of the tasks. Typically, studies vary the difficulty of one of the tasks while the other task does not change in order to study how simultaneous cognitive processing can affect posture, or how, for a given postural task, the cognitive processes can be altered. When both tasks require a certain level of control, the increase in the attentional load lead to a sharing of attentional resources in order to better perform both tasks. Apart from the division of attention, we have seen that this paradigm requires the intervention of other cognitive processes or systems such as focusing attention, inhibition, and working memory. A situation of postural threat, which can increase the inherent difficulty of the task or just the imagined consequences of a loss of balance (elevated moving platform) also requires a high level of attention. In this situation there may be a more substantial attentional load for elderly fallers or for subjects with balance impairment, who may require attention to integrate sensory information and to control posture [42]. This may lead to a deterioration of postural performance or changes in balance strategies. Cognitive impairment also modifies the relationship between posture and cognition by changing certain components of attention, working memory, or previously described executive functions. Experimental protocols derived from this theoretical knowledge make it possible to create clinical tests that predict falling and that are adapted to different patient populations (balance-impaired or cognitively-impaired older adults). There is a vast amount of information in the literature on dual-tasks, here we will detail studies that examine the relationship between cognitive components and their consequences on the control of posture and gait. These consequences can be more or less sensitive depending on the parameters used to characterize the performance of posture or gait.

Contribution of attentional mechanisms to the control of balance and gait

For a long time, maintaining postural balance and gait were considered as relatively simple tasks that use quasi-automatic sub-cortical and spinal regulations with little or no attentional resources. However, in everyday life, it is rare that a postural or locomotor task is conducted alone. It is more often associated with a cognitive activity that is more or less complex, such as listening to music or talking.

In young adults, maintaining balance requires little attentional resources. However, the use of attentional resources becomes necessary when the postural task increases in difficulty. For example, the reaction time of the secondary task increases when the subject is standing or walking as compared with sitting [50]. The increase of the attentional demand has also been reported in environmental situations where visual, vestibular or proprioceptive sensory information has been modified [94]. In difficult postural situations that require all the subject's attentional resources in order to maintain balance, postural control is modified. Subjects standing on an elevated translational platform adopted a rigidification strategy resulting in head over feet stabilization, and reducing the limits of stability during voluntary movements [112]. In dual-task situations, the cognitive task associated is disturbed and the workload, defined by NASA-TLX test, is increased (unpublished data). These modifications of postural control are found in elderly subjects in less difficult balance situations. This demonstrates an increase in the attentional load that can sometimes lead to poorly adapted postural strategies.

For elderly subjects, many studies have reported an increase in the attentional cost of posture control, even in relatively simple conditions (for review, see [55,108]). In dual-task situations, the increase in attentional load can cause elderly subjects to reach the limits of their capacity to share attention. This could explain the prioritization of one task over the other. According to Shumway-Cook et al. [88], the priority given to a task depends on multiple factors including the nature of the postural and cognitive tasks, the environmental conditions, the instructions relative to the tasks and the individual goal. In the case where attentional resources are focused on a cognitive task and where the allocation of attention to the posture is reduced, postural performance can deteriorate (e.g. [64]). These studies were conducted on subjects who were standing quietly while they performed different cognitive tasks. There are more age-related differences in balance for cognitive tasks that use the visuospatial sketchpad mechanism of working memory. Another consequence is a change in postural strategy. Subjects will adopt a more rigid posture according to the "posture first" principle [88]. In a previous study we analyzed the postural changes related to age in dual-task situations by mixing the difficulty of the postural task (static postural conditions: standing without movement, and dynamic: maintaining balance on a translational platform) and the cognitive task (spatial representation or mental calculation) [17]. In dual-task situations, young and middle-age adults improved their postural performance, which could reflect an automation of postural control. However elderly subjects had a significant alteration that could cause a fall,

which, conversely, demonstrates an enhanced cognitive control to maintain balance. These differences increase as the descriptors of postural control become more sensitive [48]. These data for elderly subjects are integrated in the model of interaction posture/attentional load. Elderly subjects can not manage the attentional cost of both tasks so they give priority to the postural task ("posture first") as a strategy to avoid falling. Young subjects who can automatically regulate their posture, focus their attentional resources on the cognitive task according to a model that we call "cognitive first". In situations with a postural threat, when potential consequences of the loss of stability increases, postural control is prioritized over the performance of the secondary task [24]. Other studies have considered the consequences of dual-tasking in elderly subjects tested in locomotor situations. Data show a reduced walking speed, an increased variability of walking pattern [79], or medio-lateral trunk sway [101]. In dual-task situations that involve memory tasks while walking, the cost of the dual-task is higher for memory performance than for walking, which suggests that the elderly give priority to walking [56]. The selection, optimization, compensation theory developed by Baltes and Baltes [11], who studied different task prioritization patterns for dual-tasks, predicts that the elderly direct their attentional resources towards the task component that they can accomplish best and that has the most validity. In this model, the adaptation that makes it possible to preserve postural balance is dependent on compensation behavior or on a revision of the goal or priority tasks [55].

These dual-task situations provide a theoretical base to explain some falls in balance-impaired older adults. For these subjects, the competition for the allocation of attentional resources in daily dual-task situations could become decisive and contribute to the pathophysiology of balance impairment. The ability to recover balance using a feet-in-place response as the primary task and verbal reaction time to auditory tones as the secondary task was more attentionally demanding in balance-impaired elderly subjects than in healthy elderly subjects [23]. Along these lines, elderly subjects with balance impairment performed worse when asked to perform obstacle avoidance while simultaneously walking and performing an auditory Stroop task [89]. The authors found that the lack of flexibility when focusing attention between two or more tasks performed simultaneously may contribute to an instability and falls for elderly adults with balance impairment. Other studies have shown similar results with subjects with vestibular impairment. Despite a unilateral vestibular impairment that is well compensated, maintaining balance in dual-task situations lowers the performance on associated cognitive tasks ([110], M_{age} 46.6 years; [82] M_{age} 48.7 years). This effect is especially important for more challenging cognitive tasks (forced choice and inhibitory tasks) [82]. According to these authors, cognitive processes most likely interfere with the processing of information that is necessary to perform postural tasks. Based on these studies we hypothesize that for these patients, cognitive processes participate in the compensation of balance impairment. Sharing attentional resources in a way that favors an automation of postural control could be the marker of good compensation in balance-impaired subjects. In general, attention seems to

be more continuously involved in postural control for all subjects with balance impairment, regardless of age.

Contribution of executive function and memory in the control of balance and gait

Few studies have examined the role of different executive functions on the control of posture and locomotion. The role of executive function has been determined by establishing correlations between postural tasks and cognitive tasks that involve executive mechanisms. In elderly subjects, Hausdorff et al. [36] compared walking performance with performance on the Stroop test (measure of inhibition) and memory tests (immediate and delayed free recall). These authors showed that subjects who performed well on the Stroop test exhibited better walking performance (lower stride time variability) than subjects who performed worse on the Stroop test. However, this relationship does not exist when comparing walking performance with verbal memory performance. In this case, walking performance was the same regardless of the performance on the memory tests. It can be noted, that from the point of view of cognitive processes, attentional load is lower in the situation where one is asked to recall words. Similar results were reported on the correlation between executive function and falls in the elderly [38]. In a longitudinal study conducted over five years, Watson et al. [104] identified associations between the evaluation of executive function and the decrease in walking speed. The authors found that no specific cognitive process can account for the slowing of walking, which suggests that a large range of cognitive processes potentially influence reduced mobility over time. The authors also observed an association between walking speed and verbal memory. All of these studies appear to indicate that executive function contributes to gait control. However, a deficit of verbal memory may be associated with a reduction of walking speed, but not walking variability.

The relationship between cognitive function and postural locomotion is also described in cognitive pathologies. For patients with Alzheimer's disease, the rate of falling increases with the progression of the dementia [90]. These effects are most likely related to the alteration of executive function, whose role is crucial for walking. Patients who suffer from Alzheimer's and dysexecutive syndrome have an increased gait variability in dual-task conditions such as backward counting [3] or repeating random numbers [87]. Significant associations between executive function and gait slowing were also reported in older people with mild cognitive impairment (MCI) [69], frontotemporal dementia [4], and idiopathic normal pressure hydrocephalus which were better detected under dual-tasking conditions. For patients with MCI, cortical control of gait is associated with a decline in the working memory. Using quantitative measures of walking could be a complementary way to evaluate the cerebral function in the pre-clinical phase at the beginning of dementia [69]. Recently it has been shown that the use of dual-tasks inspired by daily life make it possible to detect impaired executive function early with a sensitivity of 89% and a specificity of 94% [78]. The Stroop Walking Task, which is one of these daily-life-inspired tests, is similar to crossing a road with a pedestrian traffic light where the subject

must respond to a visual pictogram with a motor response (walk or stop). For elderly persons with MCI, dual-task conditions have shown that they walked more slowly, had a wider support width, and subjects who have fallen multiple times have more gait variability. It has been reported that discrimination is possible with single locomotion tasks alone and there is no added benefit in discriminating fallers from non-fallers when a secondary task is added [93]. These results indicate that for these subjects, the increased risk of falling may be caused more by sensorimotor deficits and balance impairments than cognitive deficits.

Can the dual-task paradigm be used as a diagnostic aid for fallers? The division of attentional resources in dual-task situations could explain some falls in elderly subjects without known sensorimotor or cognitive impairment. Certain posture alterations can only be observed in dual-task situations that require a sharing of attentional resources that are usually reserved for posture control. Consequently, conducting a dual-task is the basis of the development of a series of clinical tests with the goal of identifying the disturbances in walking and the risk of falling. Dual-tasks make it possible to distinguish between fallers (at least one fall in the previous year) and non-fallers. In this domain, the research of Lundin-Olsson et al. [61] has shown the utility of the sign "stops walking when talking" in the prediction of falling with a strong specificity (95%) but a weak sensitivity (48%). Subjects who stop walking when a conversation starts fall more often than those who continue to walk. Other dual-task situations made it possible to distinguish between fallers and non-fallers. For example, gait initiation performance in a situation of dual-task that consisted of counting backwards while walking. Gait initiation is a destabilizing voluntary behavior that requires moving the center of pressure backwards. In this case, fallers show smaller backward displacements than non-fallers. Limited backward displacements could be a strategy to prevent excessive imbalance [100]. It is interesting to note that it is possible to differentiate between fallers and non-fallers with a motor dual-task, such as walking with a glass of water in hand, that also requires an sharing of attentional resources. Fallers have a slower cadence and walking speed than non-fallers [98]. In dual-task situations, subjects at risk of falling demonstrate poor judgment of mobility which leads to risk-taking. This was shown with subjects placed in a situation with a virtual reality environment where participants crossed a simulated street by walking on a treadmill while listening to music or talking on the telephone. Subjects at risk for falling had more crashes with cars and took more time to cross the street when they were on the phone as compared to the control group [70]. Some dual-task tests are simple and easy to conduct. They could be added to the battery of neuropsychological tests or replace certain tests in order to create an early evaluation of walking impairment [111]. All of this research makes it possible to plan rehabilitation focused on dual-task control strategies [16].

Reinforce cognition to improve balance and gait

Attention and executive function are essential in postural control and play a role in the instability observed in certain

age-related pathologies. As we just saw, this has been reported during impairment of balance and/or executive function. For healthy elderly subjects, the onset of imbalance and the risk of falling is not only the result of an age-related alteration of sensory and motor functions that regulate balance (part 1). Cognitive aging, and specifically the reduced speed of information processing, attentional capacities, and inhibition capacities (part 2), are also important factors that are involved in the decline of balance capacities.

We have also seen that, in general, the relationship between postural and cognitive function reported in the literature focused on the deleterious effects caused by the cognitive-postural dual-task situation for elderly subjects due to additional attentional costs. Some studies examined postural-cognitive relationship differently by focusing on the consequences of an improvement of cognitive capacities on postural performance. Could cognitive training, with the goal of improving certain cognitive functions, improve postural balance?

Cognitive training is a type of intervention which focuses upon improving cognitive function (for review [1,81]). Data in healthy older adults suggest that cognitively stimulating activities have a positive effect on cognition [71,99]. Findings indicate that in older adults, in order to induce benefit transfer to untrained cognitive abilities and to maintain these benefits, it is crucial to use a training program built with complex memory or attention tasks, or a set of memory and attention tasks involving working memory and consequently associated executive processes. Training older adults in this way is more likely to show benefit transfer to untrained cognitive mechanisms than training with a simple memory task [37]. Investigating the impact of a working memory-based training (n-back tasks) in older adults, Li et al. [58] found benefits on the practiced task as well as a transfer to untrained working memory tasks. These benefits were still present three months after the end of training. Similar results reported by Buschkuehl et al. [25] also showed benefit transfer of a working memory-based training to untrained tasks. Interestingly, Borella et al. [21] investigated the transfer effects of a verbal working memory-based training program in older adults and found transfer to tasks based on similar abilities (visuo-spatial working memory and short term memory) but also to tasks based on dissimilar abilities (fluid intelligence, inhibition, and processing speed). Transfer maintenance was found at eight-month follow-up for fluid intelligence and processing speed. Stigsdotter-Neely [91] showed that memory performance was further improved in older adults who underwent multifactorial training (encoding operations, attentional training, and relaxation). Interestingly, Winocur et al. [107] and Levine et al. [54] reported that older adults who had multifactorial training (notably memory, goal management, and psychosocial skills) showed an extended benefit transfer to other cognitive tasks. Other studies have evaluated the transfer of benefits from cognitive training to activities in daily life. Training concerning the speed of information processing, memory, or reasoning has resulted in improvement in driving a car or instrumental activities such as using a telephone or managing finances [10,106]. Dual-task training programs, in which performance on a task is improved through strategies and individualized adaptive

performance feedback is provided over multiple sessions, has been shown to reduce costs associated with performing multiple concurrent tasks [47]. With this dual-task training program, transfer to other tasks for which there was no training was also observed. Interestingly for our purpose, these data suggest that dual-task training can improve general dual-task ability in younger and older adults and that attentional control can be improved in old age [18]. Taken together, these studies indicate that depending on the cognitive training used, it is possible that benefits transfer to other cognitive processes that are untrained and to other everyday tasks. Considering the positive benefits of training on cognition and the involvement of executive function and attention in the performance of gait, one can expect an impact of cognitive training gains on gait.

The transfer of benefits from cognitive training to optimize postural balance function has only recently been studied. In this context, cognitive training is based on the hypothesis that specific training of attentional resources and of certain executive function can improve the capacities of attentional sharing in postural and cognitive dual-task situations. The studies conducted in this domain have analyzed the potential benefit of training targeting certain cognitive functions on postural or locomotive performance for healthy elderly subjects.

Li et al. [57] report positive effects from cognitive dual-task training involving visual and auditory discrimination tasks. The training consisted of five sessions during which elderly subjects trained with a dual-task paradigm consisting of two visual discrimination tasks (decide the color and identity of a letter) or two discrimination tasks including one visual and one auditory task (discriminate between two sounds). This training was similar to that of the previously cited Bherer et al. [18] study, which reported an improvement in attentional control for young and older adults. Li et al. [57] report that after this type of training, subjects standing with double support on a stable platform demonstrated a better center of gravity alignment and an improvement in postural sway in single-support balance. However, the walking speed did not improve. Another study analyzed the effects of cognitive training (Mindfit computer program adapted for each subject). The authors observed an improvement in the walking speed during a dual-task of walking while talking as well as in the single task of walking [102].

The results of these studies contribute to our understanding of the alteration of postural control with aging and the interventions that can improve this. We hypothesize that personalized cognitive rehabilitation programs, modeled on the sensory-motor rehabilitation programs used in physical therapy, could provide beneficial effects on postural control. In an ongoing study, we have trained subjects with a personalized task of focused attention (visual and visuo-spatial modalities) and a cognitive-cognitive dual-task (attention task and memory task). The preliminary results show an improvement in the postural performance of trained subjects while balance capacities remain unchanged in the non-trained group [20].

Complementary studies are necessary to define the action modes and the limits of this type of training. The cognitive mechanisms by which executive functions participate in postural control are still largely unknown and there

is a lack of highly developed explanatory hypotheses. Based on the data from the literature, we can hypothesize that the improvement in the speed of processing and cognitive mechanisms such as focusing, inhibition, and management of attentional sharing in cognitive-cognitive dual-tasks, positively affect sensory information processes necessary to maintain balance. It can also lead to a better selection of the task to prioritize, as well as an improvement in the capacity of attentional sharing in a cognitive-postural dual-task. Consequently this improvement should favor a better management of dual-tasks and cause better postural balance.

Future research should investigate whether improvement of cognitive capacities can have a positive effect on the control of balance in other populations such as healthy subjects over 80 years old, or elderly subjects with attentional or balance impairment. In other words, is a minimum level of cognitive and postural capacity necessary for the effects of the treatment to be effective [55]? There is also the question of the maintaining the benefit of cognitive training programs in the long term. Though no study concerning posture and locomotion has addressed this subject, there have been positive results in long-term effects of cognitive training on cognitive function, reported up to five years after training [106].

Reinforcing cognition in order to improve posture could be one of the focuses of intervention and an important element to improve the quality of life of the elderly. Rehabilitation programs based on the improvement of cognitive capacity could be helpful for elderly persons who cannot undergo rehabilitation based on physical exercises. They could be proposed with or alternating with physical training that focuses on balance and strength.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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