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Review

Age-related differences in attentional cost associated with postural dual tasks: Increased recruitment of generic cognitive resources in older adults

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ABSTRACT

Dual-task designs have been used widely to study the degree of automatic and controlled processing involved in postural stability of young and older adults. However, several unexplained discrepancies in the results weaken this literature. To resolve this problem, a careful selection of dual-task studies that met certain methodological criteria are considered with respect to reported interactions of age (young vs. older adults) × task (single vs. dual task) in stable and unstable postural conditions. Our review shows that older adults are able to perform a postural dual task as well as younger adults in stable conditions. However, when the complexity of the postural task is increased by dynamic conditions (surface and surround), performance in postural, concurrent, or both tasks is more affected in older relative to young adults. In light of neuroimaging studies and new conceptual frameworks, these results demonstrate an age-related increase of controlled processing of standing associated with greater intermittent adjustments.
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1. Introduction

The focus of the present review is the question of whether older adults are more affected by concurrent task demands while they perform postural tasks compared with young adults and, if so, which specific conditions are more likely to produce this effect. Our guiding hypothesis is that older adults exhibit less automatic processing of posture while standing, leading to greater involvement of cognitive resources, especially when surface conditions are difficult.

Limited attentional resources have been shown to predict falls in older individuals (Faulkner et al., 2007; Hegeman et al., 2012; Montero-Odasso et al., 2012). Altered control of attentional resources is considered to reduce the ability to manage independent activities of daily living (Stuss and Levine, 2002). Some authors have even argued that dual-task performance capabilities may constitute a predictor of falls in older adults (Bergland and Wyller, 2004; Lajoie and Gallagher, 2004; Verghese et al., 2002). It is therefore a critical endeavor to determine whether the attentional demand for postural stability is altered in healthy aging or, in other words, whether maintaining a stable posture requires more cognitive resources in older relative to young adults.

The attentional cost related to the maintenance of postural stability has widely been assessed using dual-task designs (for reviews, see Boisgontier et al., 2011; Fraizer and Mitra, 2008; Lacour et al., 2008; Woollacott and Shumway-Cook, 2002). However, the interpretation of the results is not straightforward, partly due to the versatile nature of the postural processing requirements (controlled vs. automatic) and the variety among the dual-task designs that have been used (Fraizer and Mitra, 2008). Nevertheless, since all of these studies basically look into the same phenomenon, one would expect at least some degree of agreement among results. This lack of consistency in the dual-task literature partly explains some substantial critique of dual-task research in general that started in the 1980s (Navon, 1984). More recently, the review of Zijlstra et al. (2008) questioned the added value of dual over single postural task conditions for fall prediction. Stins and Beek (2012) also expressed reservations about the possibility for cognitive processes to influence postural control.

We believe that several inconsistencies could be resolved by a careful selection of dual-task studies under consideration according to methodological criteria. For the present review, we included only age-comparative studies, in which measures of single- and dual-task performances were reported for *both* tasks. This led to the exclusion of numerous studies in the secondary task tradition, in which level of performance in concurrent tasks merely producing “load” was largely left uncontrolled. Furthermore, we discuss the implications of our systematic review in the light of recent neuroimaging findings and propose new conceptual frameworks related to age differences in resource allocation and dual-tasking.

1.1. Posture

1.1.1. Controlled and automatic processing

Posture is defined as the spatial organization of the body segments (Winter, 1995). To keep a posture stable the central nervous system has to process information related to a somato-sensory-motor state, a context and a task (Peterka, 2002). The goal of this integration is to elaborate motor commands that aim at adjusting posture (Mergner and Rosemeier, 1998). The term ‘postural control’ can be misleading because postural stability does not only involve controlled processing. Maintenance of posture can be described with regard to a continuum ranging from ‘controlled to automatic’ processing (Schneider and Chein, 2003; Schneider and Shiffrin, 1977). Different levels of postural processing can be distinguished with the higher level representing totally controlled and the lower level representing automatic processing (Glover, 2005). More specifically, lower levels of processing are based on brainstem synergies (Honeycutt et al., 2009) whereas higher levels of processing rely more on the basal ganglia-cortical loop to optimize the postural response based on the current context (Jacobs and Horak, 2007). In the context of posture, the higher level consists of controlled adjustments which are typically performed when subjects intend to stand as still as possible whereas the lower level of control consists of the automatic micro-adjustments that an individual performs permanently but that mainly take place outside conscious awareness (Stins and Beek, 2012).

1.1.2. Brain correlates

More cognitive resources are being recruited during controlled relative to automatic processing of posture. This difference can be explained by a larger involvement of the cortex in controlled than in automatic processing. In contrast, automatic processing is assumed to rely more heavily on brain stem/spinal regions.

Recent studies attempted to identify brain regions involved in the control of posture during standing by using mental imagery designs during functional magnetic resonance imaging (fMRI) (Jahn et al., 2004; Zwergal et al., 2012). Results of these studies have demonstrated activations in the superior frontal gyrus, insula, middle temporal gyrus, thalamus and cerebellum while imagining a standing posture in young adults. Focusing on the cerebellum, Bernard and Seidler (2013) demonstrated that time performance in a one-legged standing balance task was associated with posterior cerebellum and Crus I volumes. Using functional near-infrared spectroscopy, Mihara et al. (2008) also showed that preparation for an external postural perturbation yielded enhanced activation in the right posterior parietal cortex and supplementary motor area, while the perturbation itself yielded activations in the prefrontal cortex. Brain activations revealed in these four studies suggested that postural stability requires higher cognitive functions (Chang et al., 2013; Desmurget et al., 2009; du Boisgueheneuc et al., 2006), integration of functional systems involved in sensory-motor processing and cognition (Chang et al., 2013; Mesulam, 1998; Miller et al., 2002), and uses internal representations (Wolpert et al., 1998).

1.1.3. Stability and processing of posture in aging

Greater postural sway in a static condition has been related to greater incidence of falls in older adults (Bergland and Wyller, 2004; Lajoie and Gallagher, 2004; Verghese et al., 2002) and is therefore considered an indicator of declined postural stability. Most of the studies assessing postural performance in static standing showed a decreased performance in healthy older adults as compared to young adults (e.g., Huxhold et al., 2006; Maylor and Wing, 1996; Prado et al., 2007; Raymakers et al., 2005; Van Impe et al., 2013). However, other studies did not report such age-related differences (e.g., Anstey et al., 1993; Bernard-Demanze et al., 2009; Doumas et al., 2008; Shumway-Cook et al., 1997; Simoneau et al., 2008; Smolders et al., 2010). Some of these latter studies concluded that mechanisms and strategies involved in postural control are similar in young and older adults. However, the absence of differences in postural stability between young and older adults is not sufficient to conclude that an age-related alteration of postural control is not evident. Indeed, as demonstrated in fMRI studies during upper and lower limb tasks, older adults may recruit additional neural resources to reach sensorimotor performance levels comparable to those obtained in the young adults (Goble et al., 2010; Heuninckx et al., 2005, 2008; Van Impe et al., 2009, 2011; Ward and Frackowiak, 2003). Therefore, to draw conclusions on the age-related alteration of postural control, assessing postural stability *per se* is not sufficient. It is also necessary to directly or indirectly assess the central processing associated with this performance in order to reveal potential differences in the recruitment of neural resources during standing.

The study of Zwergal et al. (2012) associating mental imagery designs with fMRI, demonstrated age-related increases in activation across the frontal, temporal and occipital cortices in older relative to young adults. These results suggested age-related alteration of central processing during standing. Even though such mental imagery paradigms are very informative, these age-related differences in brain activation may also be partially explained by differences in imagery performance that are difficult to quantify. This methodological limitation calls for other ways to test the age-related alteration of the central processing of posture. One of these ways is the dual-task design that allows assessing how much attention is involved in the performance of a given task.

1.2. Attention and dual-task performance

1.2.1. Central concepts

Although attention is often associated with consciousness and/or effort (Kahneman, 1973; Posner and Dehaene, 1994), the study of Naccache et al. (2005) demonstrated that these concepts are independent. Attention has been initially defined as a cognitive process controlling for the level of significance allocated to stimuli (Kahneman, 1973). Corbetta and Shulman (2002) suggested this process was driven by a dynamic interaction between cognitive factors reflecting knowledge, expectation and current goals, as well as sensory factors reflecting context and tasks. Attention has different functions: focusing, selecting, and/or inhibiting the available stimuli (Rogers, 2006). Baddeley and Hitch (1974) proposed that the cognitive process of attention was part of a "control executive" supervising lower-level systems. Indeed, attention is a cornerstone of a cluster of so-called executive functions also composed of volition, self-awareness, planning, response inhibition and response monitoring (Yogev-Seligmann et al., 2008). This cluster integrates representational, somatosensory and motor components to cognitively produce and modulate behavior. Altered attention would therefore have critical consequences for behavior. Norman and Shallice (1986) distinguished lower- (contention scheduling) and higher-levels of attention (supervisory attentional system). The former is used to deal with familiar and automatic situations whereas the latter can be of use to solve more challenging and unique situations.

The typical study design used to examine executive functions and more specifically, to assess the attentional resources allocated to a task of interest is the dual-task design (Della Sala et al., 1995). Initially, dual tasks were used to study limitations in attention and multi-task interference (Brown et al., 1969), but the paradigm was soon picked up as an indirect approach to assess the degree of automaticity in performing a main task by studying performance level on a concurrent task (Schneider and Shiffrin, 1977). In this latter context, a dual-task design mainly aims at contrasting two groups in a relative way on the basis of the differences observed between single- and dual-task conditions to extrapolate potential differences in the ratio of attentional capacity to a task cost. Dual-tasks have also been used to discuss the existence of an independent cognitive resource for performing more than one task at a time and, at the same time, to potentially account for behavioral impairment in central diseases or brain traumas (Baddeley and Della Sala, 1996). Imaging studies provided more specific insights into the anatomical and functional structure of attention and dual tasking.

1.2.2. Brain correlates

Attention has shown to be partially segregated into two brain networks (Fox et al., 2006; Shulman et al., 2009) evoking the neuropsychological model of Norman and Shallice (1986). Studies on visuo-spatial attention revealed that areas most consistently activated when individuals pay attention to a location in anticipation of a stimulus are the dorsal parietal and dorsal frontal cortex (Corbetta and Shulman, 2002). Specifically, activation was evidenced in the posterior intraparietal sulcus, the superior parietal lobule, the postcentral sulcus, the precentral sulcus and the superior frontal sulcus. This bilateral 'dorsal attention network (DAN)' is involved in top-down allocation of attention. Conversely, when salient sensory stimuli are detected outside the current focus of processing, the right-lateralized 'ventral attention network (VAN)' acts as a circuit-breaker and updates the allocation of attention (Corbetta and Shulman, 2002; Fox et al., 2006). Specifically, activations evidenced in the presence of low-frequency stimuli that reorient attention include the temporo-parietal junction and the ventral frontal cortex. In view of the well supported anterior-posterior gradient referring to a more pronounced age-related degeneration in anterior brain regions, areas involved in cognition and executive control are relatively more affected than others (Bennett et al., 2010; Coxon et al., 2012; Lu et al., 2013; Sullivan and Pfefferbaum, 2006; Van Impe et al., 2012).

There is an ongoing debate concerning the brain correlates of dual tasking. Some studies supported the existence of cortical areas specifically activated during dual tasking (D'Esposito et al., 1995; Dreher and Grafman, 2003) whereas other studies rejected the idea of there being any dual-task specific area in young (Adcock et al., 2000; Bunge et al., 2000; Dux et al., 2006; Klingberg, 1998; Rémy et al., 2010) and older adults (Van Impe et al., 2011). Nevertheless, all studies demonstrated that dual tasking yielded greater activation relative to both single tasks in the prefrontal (Adcock et al., 2000; D'Esposito et al., 1995; Dux et al., 2006) and/or parietal cortex (Bunge et al., 2000; Collette et al., 2005; Dreher and Grafman, 2003; Rémy et al., 2010; Szameitat et al., 2002). Recently, Wu et al. (2013) demonstrated an additional activation of the cerebellum for dual-task performance involving tapping and letter counting tasks. This activation was connected to the necessity for integrating different networks to perform dual-tasking properly. Neuropsychological studies also intended to explain the physiology of dual tasking.

1.2.3. Attention as a resource in dual-task contexts

Extant models of multi-tasking have their roots in classical capacity theories (Kahneman, 1973) as well as in processing-bottleneck theories (Pashler, 1994). These theories have been used to explain findings in dual-task studies. Although different in metaphor, capacity and bottleneck models share many similarities and predictions with respect to multi-tasking. Hartley and colleagues (e.g., Hartley and Little, 1999; Hartley, 2001) argued that older adults do not have a specific dual-task deficit. Their disadvantage rather arises at the level of an output bottleneck, that is, from the need for parallel response production in concurrent tasks. However, more recent studies (e.g., Krampe et al., 2010) found pronounced dual-task costs in older adults in continuous tasks without concurrent response production. From this, the assumption of an output bottleneck as a sole cause for age-related deficits in multi-tasking does not seem tenable.

Most accounts of multi-tasking locate the primary causes of interference at central processing levels and they typically refer to attention as a critical resource or capacity. The capacity sharing model of attention assumes that to adapt to an increased level of task difficulty, individuals have to increase the level of attention allocated to this task. This increased attention is implicitly related to an increased degree of cognitive processing of this task. Therefore, increasing allocation of attention is assumed to improve performance. In its original version, degradation of performance observed in multi-tasking is explained by task competition for the limited capacity of a general, single pool of resources (Kahneman, 1973; Tombu and Jolicoeur, 2003). A later version, the multiple resources model (Navon and Gopher, 1979; Wickens, 2008; Wickens et al., 1983), proposes resource competition on multiple dimensions, the most critical one being the processing stage, i.e., the input, processing and output requirements for which attention could be required. More recently, the capacity sharing model has been amended by the constraint action theory (Wulf and Prinz, 2001). This version emphasizes that increased attention does not necessarily lead to better task performance. Indeed, studies manipulating internal vs. external locus of attention (Wulf et al., 2001) suggested that focusing attention on a highly automated behavior, such as postural control, could interfere with the automatic control processes rather than improve them. In the same line, the study of Bernard and Seidler (2013) demonstrated that a larger regional cerebellar volume implicated in cognitive tasks (Crus I) was associated with poorer balance performance in young and older adults. These theories all refer to interference between tasks.

1.2.4. Specific and generic interference

Two types of interference have been described to explain the degradation of performance when two tasks are performed concurrently: structural and capacity (Kahneman, 1973; Navon and Gopher, 1979). Structural interference refers to competition for common input, output, and/or central processing resources whereas capacity interference is inferred when the possibility for structural interference is ruled out, referring to limitations in the general processing capacity (Schmidt and Lee, 2005). However, tasks that are seemingly totally independent may still recruit similar neural resources, as medical imaging studies have demonstrated (Van Impe et al., 2011). This may particularly be the case for brain structures that have more generic functions (e.g., association areas including prefrontal and parietal structures) whereas it is less likely for primary areas (such as M1 and S1).

Therefore, and based on the suggested absence of cortical areas that would be uniquely activated in dual- relative to single-task performance conditions, we propose that the only interference that may emerge between tasks is ultimately structural interference in terms of shared brain resources. We also propose to divide this structural interference on the basis of the functional specificity assigned to the brain areas involved, i.e., whether they are primary (inducing specific interference) or association (inducing generic interference) brain areas. The assumption underlying the dual-task paradigm would then be that the more association/generic areas are involved in a task, the greater the intrinsic difficulty in performing this task. In this context, the concurrent task aims at imposing an additional load to the generic areas to indirectly reveal how much the latter are involved in the main task. This indirect analysis of generic areas is only possible and valid when the overlap in primary (sensory and motor) resources between the two tasks (specific interference) is avoided as much as possible. Indeed, this specific interference would produce dual-task effects unrelated to the intrinsic difficulty of the task and therefore prevent any conclusion in this regard.

1.3. Aging and the attentionnal cost of postural stability

Many studies have addressed the issues of attention and posture during standing in relation to aging (Table 1), mainly to test a modification in a controlled/automatic ratio of processing. However, the conclusions that can be extracted from the literature's results are not consistent. Specifically, most of the studies have demonstrated an effect of age on the attentional cost associated with maintaining posture (Berger and Bernard-Demanze, 2011; Bernard-Demanze et al., 2009; Brown et al., 1999; Dault and Frank, 2004; Granacher et al., 2011; Lajoie et al., 1996; Marsh and Geel, 2000; Raymakers et al., 2005; Swan et al., 2004; Teasdale and Simoneau, 2001; Teasdale et al., 1993). Still, a non-negligible number of studies have failed to provide evidence for such an age-related difference (Dromey et al., 2010; Melzer et al., 2001; Prado et al., 2007; Shumway-Cook et al., 1997; Van Impe et al., 2013; Weeks et al., 2003; Yogev-Seligmann et al., 2013). Among the studies showing an effect of age, this finding was mainly related to a decline from the single- to the dual-task condition in the older as compared to the young adults (e.g., Marsh and Geel, 2000; Swan et al., 2004; Teasdale and Simoneau, 2001). Nonetheless, some of these effects were only explained by improvements from the single- to the dual-task condition in young (Berger and Bernard-Demanze, 2011) or older adults (Simoneau et al., 2008; Swan et al., 2004). Among the

Table 1
Postural studies that used a dual-task design in older adults. Highlighted in grey are the studies which met the imposed criteria of the review. (DT = dual-task performance; No = no data available; OA = older adults; ST = single-task performance; YA = young adults; x = data available).

Study	Group		Secondary task		Postural task	
	OA	YA	ST	DT	ST	DT
Teasdale et al. (1993)	x	x	x	x	x	No
Lajoie et al. (1996)	x	x	x	x	No	No
Maylor and Wing (1996)	x	x	x	x	x	x
Shumway-Cook et al. (1997)	x	x	No	x	x	x
Brown et al. (1999)	x	x	No	x	x	x
Marsh and Geel (2000)	x	x	x	x	No	x
Morris et al. (2000)	x	No	No	x	x	x
Rankin et al. (2000)	x	x	No	No	x	x
Shumway-Cook and Woollacott (2000)	x	x	x	x	x	x
Brauer et al. (2001)	x	No	No	x	x	x
Maylor et al. (2001)	x	x	x	x	x	x
Melzer et al. (2001)	x	x	No	x	x	x
Redfern et al. (2001)	x	x	x	x	x	x
Teasdale and Simoneau (2001)	x	x	x	x	No	x
Brown et al. (2002)	x	No	x	x	No	No
Redfern et al. (2002)	x	x	No	x	No	x
Weeks et al. (2003)	x	x	x	x	x	x
Dault and Frank (2004)	x	x	No	x	x	x
Lajoie (2004)	x	No	No	x	No	x
Müller et al. (2004)	x	x	No	x	x	x
Swan et al. (2004)	x	x	No	x	x	x
Albinet et al. (2006)	x	No	x	x	x	x
Raymakers et al. (2005)	x	x	No	x	x	x
Huxhold et al. (2006)	x	x	x	x	x	x
Rapp et al. (2006)	x	x	x	x	x	x
Mahboobin et al. (2007)	x	x	No	No	x	x
Pajala et al. (2007)	x	No	No	x	x	x
Prado et al. (2007)	x	x	No	x	x	x
Doumas et al. (2008)	x	x	x	x	x	x
Simoneau et al. (2008)	x	x	x	x	x	x
Bernard-Demanze et al. (2009)	x	x	x	No	x	x
Doumas et al. (2009)	x	x	x	x	x	x
Swanenburg et al. (2009)	x	No	No	No	x	x
Dromey et al. (2010)	x	x	x	x	x	x
Heiden and Lajoie (2010)	x	No	No	x	No	x
Kang and Lipsitz (2010)	x	No	No	x	x	x
Li et al. (2010)	x	No	x	x	x	x
Mendelson et al. (2010)	x	x	x	x	No	No
Smolders et al. (2010)	x	x	x	x	x	x
Swanenburg et al. (2010)	x	No	x	x	x	x
Berger and Bernard-Demanze (2011)	x	x	No	No	x	x
Granacher et al. (2011)	x	x	No	No	x	x
Hegeman et al. (2011a)	x	No	No	No	x	x
Hegeman et al. (2011b)	x	No	No	No	x	x
Hiyamizu et al. (2012)	x	No	No	x	No	x
Haggerty et al. (2012)	x	No	No	x	x	x
Kang et al. (2013)	x	No	No	x	x	x
Van Impe et al. (2013)	x	x	x	x	x	x
Yogev-Seligmann et al. (2013)	x	x	x	x	x	x

studies that evidenced an effect of age due to a decline in the performance of the older adults relative to the young adults from single- to dual-task conditions, the decline was mainly observed in the more challenging ones (Lajoie et al., 1996; Teasdale et al., 1993) but some exceptions were noted (Raymakers et al., 2005). It is often argued that the reasons for this lack of consistency in the literature are the multiple conditions which have been used in the different dual-task designs (Fraizer and Mitra, 2008). However, since the studies reported in the present paragraph are all assessing the same phenomenon, there should be more agreement among results, whatever the conditions. Therefore, the present review does not intend to describe the study differences that may have contributed to the vast discrepancies in the literature. This has already been done in a recent review of Fraizer and Mitra (2008). Conversely, our attempt is to identify a converging picture across the discrepancies within the literature. To this aim, we performed a systematic review focusing on studies that met specific methodological criteria.

2. Methods

2.1. Search strategy

A computer based search was carried out using the electronic bibliographic databases: PubMed, Cochrane, EMBASE, and by checking references found in retrieved articles. The search included papers from 1990 until 2013 using the following key words: posture and aging/aged and executive functions; posture and aging/aged and attention; posture and aging/aged and working memory; posture and aging/aged and dual task/tasking; posture and aging/aged and cognition.

2.2. Study selection

In postural studies using dual-task designs, participants of an experimental group and a control group perform the postural task and a concurrent task separately (single tasks, ST) and concurrently (dual task, DT). In this review, studies assessing older but not young adults were excluded.

To accurately assess age-related differences in the attentional cost associated with postural control, it is critical to have access to levels of performance in both the postural and concurrent task, in both single- and dual-task conditions, for both young and older adults. For instance, if a dual-task design evidences an age-related decline in postural stability from the single task to the dual task, this would not be sufficient to conclude that older adults' performance is more affected by dual tasking. Indeed, results in the concurrent task could unmask an age-related difference in the dual-task strategy (e.g., an age-related improvement in the concurrent task). Therefore, to be complete and allow an accurate interpretation of the results, a dual-task design should report at least eight measures (i.e., for young and older adults: postural and concurrent task performances in single and dual conditions). Studies that did not report these eight measures were excluded from this review.

3. Results

Database and reference searches identified 53 studies for consideration. Abstract examination identified 4 reviews, which were excluded from further consideration. After applying the exclusion criteria, 14 studies were considered for the review (Table 1).

The selected studies reported in Table 2 revealed results of the 2 age (young adults vs. older adults) × 2 task (ST vs. DT) interaction in stable (Table 2A) and unstable (Table 2B) conditions of posture. The result of this interaction indicated whether the attentional cost of an additional task differentially affected young and older adults. To give an indication about the direction (decline vs. improvement) and the amount of performance alteration from the single-task to the dual-task condition, dual-task costs (DTCs) for postural and concurrent performances were computed in young and older adults according to the following formula: $[DTC = (DT - ST)/ST] \times 100$ when an increase in the metric was related to a performance decline (e.g., greater ellipse area) and $[DTC = (ST - DT)/ST] \times 100$ when an increase in the metric was related to a performance improvement (e.g., increased number of correct items) (Doumas et al., 2008; Rapp et al., 2006). Positive and negative DTC values were therefore always respectively obtained in the case of increased and decreased costs, from single- to dual-task conditions. The advantages of using this proportional metric were that (a) age-related differences in baseline performance are taken into account and (b) results from different types of variables can be compared across studies. As controlling for cognitive impairment is critical in dual-task designs, we also reported the mini-mental state examination (Folstein et al., 1975) and Montreal cognitive assessment (Nasreddine et al., 2005) scores when available.

3.1. Results on age-related differences in stable conditions

3.1.1. Performance on the postural task

When participants were instructed to remain as still as possible in the conditions of stable surface and surround, the age (young adults vs. older adults) × condition (ST vs. DT) interaction was shown to be significant ($p < 0.05$) with respect to the postural performance in 2 out of 11 studies reporting *absolute data* (Maylor and Wing, 1996; Maylor et al., 2001) (Table 2A). These interactions associated with greater DTCs in older relative to young adults were evidenced in the Brooks' spatial task and a backward digit recall task. In the latter, participants are asked to repeat sequences of 3 to 5 digits in a reverse order. The 9 other studies used various additional tasks (digit generation, counting, Brooks non-spatial, motor task, reaction times, spatial memory, mental rotation, n-back task) and only showed non-significant interactions (Huxhold et al., 2006; Redfern et al., 2001; Shumway-Cook and Woollacott, 2000; Simoneau et al., 2008; Smolders et al., 2010; Van Impe et al., 2013; Weeks et al., 2003).

Testing the age-related absolute differences in performance may be preferred to account for clinical differences because it does not require transformation of the raw data. However, some authors have chosen to use *relative/proportional values* primarily due to limitations in contrasting the absolute values in single- and dual-task performance between young and older adults. Indeed, the studies of Rapp et al. (2006) and Doumas et al. (2008) did not test the interaction of absolute values but compared postural DTCs between young and older adults. Both of these studies used digit n-back tasks where participants are asked to name single digits presented successively. Challenge of the task is increased by asking the participants to name the stimulus presented n times before the current stimulus. Results showed that young adults maintain higher levels of postural performance than older adults with decreased CoP (center of feet pressure) areas (7% vs. 22% and 1% vs. 38% postural DTCs, respectively). Although 7 out of 11 studies did not show significant age-related differences in the cost of posture during standing, a convergence across the results of all studies can be noticed. Indeed, when looking at the postural DTCs related to all analyzed dependent variables of all studies, 30 were greater in older as compared to young adults whereas they were lower for only 4 dependent variables (not always significant).

3.1.2. Performance on the concurrent task

In the conditions of a stable surface and surround, none of the studies reported in Table 2A evidenced a significant age (young adults vs. older adults) × condition (ST vs. DT) interaction with respect to performance on the concurrent task.

When comparing the concurrent DTCs between young and older adults, the study of Rapp et al. (2006) showed that young adults maintained higher levels of concurrent task performance from ST to DT as compared to older adults (0% vs. 9%). Although mainly not significant, there was still an agreement across dependent variables toward greater concurrent DTCs in older adults relative to young adults (10 greater vs. 5 lower).

To summarize findings in stable conditions, the 2 studies demonstrating an age-related effect of dual tasking on postural stability (Maylor and Wing, 1996; Maylor et al., 2001) together with the 2 studies demonstrating higher postural DTCs in older relative to young adults (Rapp et al., 2006; Doumas et al., 2008) suggest a tendency toward greater attentional resources allocated to postural control in older as compared to young adults. Conversely, only one study (Rapp et al., 2006) suggests such a tendency for the concurrent task. The lack of significance and consistency in the present results is in line with the review of Zijlstra et al. (2008) that questioned the added value of dual balance tasks for fall prediction. However, as suggested by the gait literature, more challenging conditions in the main task may be required to demonstrate stronger effects of aging (Bock, 2008).

3.2. Results on age-related differences in unstable conditions

3.2.1. Performance on the postural task

In the conditions of *dynamic* surface and/or visual surround, the age (young adults vs. older adults) × condition (ST vs. DT) interaction was significant in 3 out of 3 studies reporting absolute data with greater DTCs in older relative to young adults (Shumway-Cook and Woollacott, 2000; Smolders et al., 2010; Redfern et al., 2001) (Table 2B). Yet, the study of Shumway-Cook and Woollacott (2000) did not show any interaction when the complexity of the task was increased via a visual condition only (eyes closed or visual motion, i.e., a vertical-line stimul moving horizontally on a screen) or a surface condition (sway-referenced surface, i.e., rotation of the surface

Table 2
Dual-task costs and significance (highlighted in grey) of the 2 age groups (YA vs. OA) × 2 tasks (ST vs. DT) interactions in stable (A) and unstable (B) conditions. (AP = antero-posterior; DT = dual-task performance; DTC = dual-task cost; ML = medio-lateral; MMSE = mini mental state examination; MoCA = Montreal cognitive assessment; Scores superior than 26 reflect no dementia both in terms of MMSE and MoCA; na = non-available or non-applicable; NS = non-significant; OA = older adults; ref.=referenced; RT = reaction time; SD = standard deviation; ST = single-task performance; YA = young adults; * $p < 0.05$).

A. Stable conditions

Study	Subjects	Mean age ± SD	MMSE/MoCA	Concurrent task				Postural task			
				Type	DTC (%)		Age × Task interaction	Dependent Variable	DTC (%)		Age × Task interaction
	YA/OA	YA/OA	OA		YA	OA			YA	OA	
Maylor and Wing (1996)	19/19	57 ± 2/77 ± 2	na	Digit generation	3	5	NS	Weight distribution SD	−4	−3	NS
				Brooks' spatial	3	12	NS		−8	11	*
				Backward digit recall	1	3	NS		−14	1	*
				Silent counting	−3	−2	NS		−7	1	NS
				Backward counting aloud	−5	0	NS		2	11	NS
Shumway-Cook and Woollacott (2000)	18/18	35 ± 8/75 ± 6	na	Choice RT	na	na	NS		na	na	NS
Maylor et al. (2001)	11/12	22 ± 2/74 ± 3	na	Brooks' non spatial	na	na	NS	CoP velocity	23	18	NS
								ML CoP SD	108	43	NS
								AP CoP SD	6	23	NS
				Brooks' spatial	na	na	NS	CoP velocity	−10	9	NS
								ML CoP SD	0	75	*
								AP CoP SD	17	5	NS
Redfern et al. (2001)	18/18	23 ± 2/74 ± 3	na	RT	12	−1	na	RMS	−23	17	NS
				Inhibition RT	3	−1	NS		−33	11	NS
Weeks et al. (2003)	9/9	24 ± 3/72 ± 3	na	10% max pinch	na	na	NS	CoP velocities and path lengths	na	na	NS
				Additions and substractions	na	na	NS		na	na	NS
Rapp et al. (2006)	10/10	24 ± 3/70 ± 6	29 ± 1	Digit 2-back	0	9 (*)	na	CoP area	7	22 (*)	na
Huxhold et al. (2006)	20/19	25 ± 3/70 ± 3	na	Watching digits	na	na	na	CoP area	−50	−21	NS
								Ln CoP area	−45	−12	NS
								Ellipse area	−39	−28	NS
								RMS-ML	−−21	−11	NS
				Choice RT	3	−3	NS	CoP area	−25	15	NS
								Ln CoP area	−26	7	NS
								Ellipse area	−16	14	NS
								RMS-ML	5	18	NS
				Digit 2-back	0	12	NS	CoP area	0	46	NS
								Ln CoP area	−30	24	NS
								Ellipse area	−16	25	NS
								RMS-ML	18	40	NS
				Spatial 2-back	3	8	NS	CoP area	17	44	NS
								Ln CoP area	−4	18	NS
								Ellipse area	8	16	NS
								RMS-ML	68	30	NS
Doumas et al. (2008)	18/18	22 ± 2/71 ± 3	29 ± 1	Digit 2-back	−3	2	NS NS	Ellipse area	1	38 (*)	na
Simoneau et al. (2008)	8/8	24 ± 2/74 ± 6		Digit string memory	46	17	NS NS	CoP velocity	−12	−7	NS
Smolders et al. (2010)	24/23	25 ± 4/68 ± 4		Spatial memory	4	2	NS NS	Ellipse area	17	23	NS
Van Impe et al. (2013)	15/25	22 ± na/71 ± na	≥26	Mental rotation task	13	20	NS	Log path length	13	20	NS

Shumway-Cook and Woollacott (2000)	18/18	35 ± 8/75 ± 6	na	Eyes closed	Choice RT	na	na	NS	CoP path length	na	na	NS
				Visual motion		na	na	NS		na	na	NS
				Sway-ref surface		YA < OA		*	na	na	NS	
				Sway-ref surface + eyes closed		YA < OA		*		YA < OA		*
				Visual motion + sway-ref surface		YA < OA		*		YA < OA		*
Redfern et al. (2001)	18/18	23 ± 2/74 ± 3	na	Sway ref surface	RT	15	10	na	RMS	−7	8	NS
					Inhibition RT	7	1	NS		−15	3	NS
				Sway-ref surface and visual surround	RT	57	33	na	RMS	−2	14	*
					Inhibition RT	18	22	NS		−5	29	*
Rapp et al. (2006)	10/10	24 ± 3/70 ± 6	29 ± 1	Moving platform	Digit 2-back	0	13 (*)	na	CoP area	9	14 (NS)	na
Doumas et al. (2008)	18/18	22 ± 2/71 ± 3	29 ± 1	Sway-ref surround	Digit 2-back	3	−2	NS	Ellipse area	14	6 (NS)	na
				Sway-ref surface		4	12	*		−12	13 (NS)	na
Simoneau et al. (2008)	8/8	24 ± 2/74 ± 6	na	Tandem stance	Digit string memory	17	21	NS	CoP velocity	−10	−27	*
Doumas et al. (2009)	8/10	27 ± 2/67 ± 3	>28	Moving platform	Digit 2-back	1	2	NS	Ellipse area	8	8 (NS)	na
					Digit 3-back	11	9	NS		8	20 (*)	na
Dromey et al. (2010)	7/10	25 ± 2/70 ± 12		Rise to toes	Speaking	na	na	NS	CoP velocity	−14	7	NS
Smolders et al. (2010)	24/23	25 ± 4/68 ± 4	>26	Moving platform	Spatial memory	4	1	NS	Ellipse area	12	19	*
Yogev-Seligmann et al. (2013)	21/15	26 ± 2/75 ± 5	27 ± 2	Tandem stance	Verbal fluency	−14	−41	NS	CoP displacement	−14	0	NS
									CoP velocity	5	11	NS
									CoP area	−16	1	NS

of support in the sagittal plane in proportion to the participant's center of mass sway angles which aims at reducing the proprioceptive input). The interaction appeared when these two complex conditions were administered concurrently (sway-referenced surface + eyes closed; sway-referenced surface + visual motion). These results suggest that increasing the complexity of either the visual input or the surface condition was insufficient to increase the sensitivity of the dual-task design to aging. This result is supported by the study of Redfern et al. (2001) that failed to demonstrate any age-related difference when surface instability was increased (sway-referenced surface) but the difference did emerge when both proprioceptive and visual inputs were reduced using the combined sway-referenced surface and visual surround (i.e., rotation of the surface of support + rotation of the visual surround in the sagittal plane in proportion to the participant's center of mass sway angles). Nevertheless, the study of Smolders et al. (2010) also found an age-related difference when only the complexity of the surface condition was increased (moving platform) in association with a spatial memory task. This result suggests that the dual-task design's sensitivity could also be improved by only increasing the difficulty of the surface condition when the concurrent task is a sufficiently complex memory task. However, increasing the difficulty of the standing posture while keeping the surface and surround *static* (tandem stance or rise to toes) appeared not to be sufficiently destabilizing to increase the sensitivity of the dual-task design, as underscored by the absence of an age-related increase in dual-task costs (Dromey et al., 2010; Simoneau et al., 2008; Yogev-Seligmann et al., 2013). Finally, no postural age-related effect was evident when the difficulty of the task was increased through visual manipulations only.

When comparing the postural DTCs between young and older adults, the studies of Rapp et al. (2006) and Doumas et al. (2009) did not reveal age-related differences in a moving platform condition associated with a digit 2-back task (9% vs. 14% and 8% vs. 8%, respectively), but increasing the difficulty of the concurrent task (3-back) increased the age-related difference in postural DTCs (8% vs. 20%) (Doumas et al., 2009). The study of Doumas et al. (2008) did not explicitly report the statistical differences between young and older adults for postural DTCs but the results suggested no age-related differences in a sway-referenced visual surround (14% vs. 6%) but only in a sway-referenced surface that reduces the proprioceptive input (−12% vs. 13%). Again, there is a strong but not always significant agreement across dependent variables of all studies toward greater postural DTCs in older adults relative to young adults (14 greater vs. 2 lower and 1 equal).

3.2.2. Performance on the concurrent task

In conditions of an unstable surface and/or visual surround, the 2 age (young adults vs. older adults) × 2 condition (ST vs. DT) interaction was significant in 2 out of 8 studies reporting absolute data with greater DTCs in older relative to young adults (Doumas et al., 2008; Shumway-Cook and Woollacott, 2000) (Table 2B). The study of Shumway-Cook and Woollacott (2000), using a choice reaction time task, did not demonstrate any interaction when the complexity of the task was increased via a visual condition (eyes closed; visual motion). However, the interaction appeared when the surface was unstable, irrespective of the visual condition (sway-referenced surface; sway-referenced surface + eyes closed; sway-referenced surface + visual motion). These results were supported by the data of Doumas et al. (2008) using a digit 2-back task and evidencing an interaction in a sway-referenced surface condition but not in a sway-referenced visual surround condition. Again, results of these two studies suggest that the sensitivity of a dual-task design to aging effects is enhanced by increasing the surface instability but not by degrading the visual condition. Nevertheless, the remaining 6 studies failed to demonstrate a significant age × task interaction (Doumas et al., 2009; Dromey et al., 2010; Redfern et al., 2001; Simoneau et al., 2008, 2010; Yogev-Seligmann et al., 2013).

One study only compared cognitive DTCs between young and older adults (Rapp et al., 2006). Using a moving surface condition associated with a 2-back task, this study showed that young adults maintained higher levels of cognitive performance from ST to DT as compared to older adults (0% vs. 13%). Considering all studies, concurrent DTCs were larger in older adults for 8 dependent variables whereas they were lower in 7 (not always significant).

In sum, the results obtained under unstable conditions of support and/or visual surround suggest a significant age-related effect of dual tasking that is indicative of an increased allocation of attention to postural processing for older relative to young adults.

4. Discussion

4.1. Stable vs. unstable conditions

This review was aimed at demonstrating the age-related differences in processing associated with postural dual tasks. Taken together, the studies summarized in Table 2 show that older adults are essentially able to manage a postural dual task as well as younger adults in stable conditions of support and surround, although there is a clear (but often non-significant) trend toward greater postural DTCs in older as compared to young adults (Table 2A). However, when the complexity of the postural task was increased in *dynamic* surface conditions, all studies showed that either the concurrent task performance (Rapp et al., 2006), the postural performance (Doumas et al., 2009; Redfern et al., 2001; Smolders et al., 2010) or both (Doumas et al., 2008; Shumway-Cook and Woollacott, 2000) were more affected in the older adults as compared to the young adults (Table 2B). Increasing the complexity of the *static* posture (tandem stance; rise to toes) was not challenging enough to unmask an age-related increase in dual-task costs (Dromey et al., 2010; Simoneau et al., 2008; Yogev-Seligmann et al., 2013). Crucially, all of the 9 studies reported in Table 2B used concurrent tasks that recruit primary brain structures that are likely not specifically involved in the postural control of standing (reaction time, n-back, digit memory, spatial memory) thus ruling out the possibility for specific interference. As a consequence, the origin of interference may have stemmed from the necessity for sharing association brain areas (generic interference). Therefore, the results reported in this review evidence an age-related increase in the allocation of attentional resources for maintaining the stability of posture. In other words, these results suggest that processing of posture becomes more controlled (cognitive) and less automatic with aging. More generally, this is consistent with the view proposed in studies outside the postural domain that aging is associated with cognitive penetration into action control to overcome age-related degenerative processes (Heuninckx et al., 2005).

Furthermore, these results also suggest that increasing the somatosensory challenges (especially via platform movement), influences the sensitivity of the dual-task design to aging. In other words, alteration of the support surface conditions (Doumas et al., 2008, 2009; Rapp et al., 2006; Shumway-Cook and Woollacott, 2000; Smolders et al., 2010) promotes increased sensitivity to age-related deficits in dual tasking. This sensitivity is even more enhanced when surface alterations are associated with visual alterations (Doumas et al., 2008; Redfern et al., 2001; Shumway-Cook and Woollacott, 2000). Conversely, manipulating the visual information only (eyes closed, visual motion, sway-referenced surround) does not appear to increase the sensitivity to age-related deficits in dual tasking (Doumas et al., 2008; Shumway-Cook and Woollacott, 2000). However, the visual surround manipulations used in the studies reported in Table 2B may not be sufficiently challenging. Therefore, the possibility for more sophisticated virtual visual surrounds to improve the dual-task designs' sensitivity to aging should not be ruled out.

The necessity for the main (postural) task to be sufficiently challenging is also confirmed by the gait literature (Bock, 2008). In addition, Doumas et al. (2009) suggested that increasing the difficulty of the concurrent task (2-back vs. 3-back task) also increases the sensitivity of the dual-task design to aging.

4.2. Impact of the concurrent task

As outlined before, concurrent tasks should be sufficiently difficult in order to reach/exceed the neural resource limit and should avoid specific interference (involving primary brain areas). Consequently, the choice of the type of concurrent task seems to be critical especially in stable conditions of support as only the Brook's spatial task and the backward digit recall revealed age-related differences in dual-task costs (Maylor and Wing, 1996; Maylor et al., 2001). All the other types of concurrent task failed to reveal such differences (digit generation, counting, Brooks non-spatial, motor task, reaction times, spatial memory, mental rotation, n-back task). However, in the studies of Maylor and collaborators (1996; 2001), dementia could also have been the main factor accounting for the age-related differences in dual-task costs as these studies did not control for it (Table 2A).

In unstable conditions of support, the nature of the concurrent task appears to be less critical as different types of task, even some of those failing to reveal age-related differences in stable conditions, demonstrated an effect of aging on the processing of posture (n-back, reaction time, digit string memory). In addition, most of these studies controlled for dementia, especially the one using the n-back tasks (Table 2B). Nevertheless, some tasks still failed to reveal an age-related difference in dual-task costs (speaking, verbal fluency) thereby highlighting the necessity for sufficiently challenging concurrent tasks.

4.3. Age-related increase in the minimum level of controlled processing of posture

In a single-task context, previous studies in young adults demonstrated that the automatic processing of posture was more stable [e.g., as determined by shorter CoP path length (Siu and Woollacott, 2007) or lower CoP frequency responses (McNevin and Wulf, 2002; Wulf et al., 2001)] than when participants were explicitly instructed to focus on their postural stability (i.e., controlled processing). No such effect has ever been reported in healthy older adults. Therefore, the hypotheses emerge that for older adults (1) the automatic processing is not more efficient than the controlled one and/or (2) their minimal required level of controlled processing is higher as compared to the young adults. The first hypothesis would imply that with aging, either controlled processing improves or automatic processing declines. The former is unlikely since the ability to perceive and correct fine disturbances decreases with age (Thaler, 2002; Boisgontier and Nougier, 2013). Accordingly, a decline in the automatic processing of posture is considered more likely and would actually give way to the second hypothesis.

This newly proposed concept of an age-related increase in the minimum level of controlled processing of posture (partly due to an alteration of automatic processing) would explain that young adults maintain or even improve their postural performance from single- to dual-task conditions (Dault et al., 2001; Doumas et al., 2008; Huxhold et al., 2006; Maylor and Wing, 1996; Redfern et al., 2001; Simoneau et al., 2008; Yogev-Seligmann et al., 2013) whereas older adults' postural performance often declines (e.g., Doumas et al., 2008; Maylor et al., 2001; Rapp et al., 2006; Redfern et al., 2001; Smolders et al., 2010; Van Impe et al., 2013). Such tendencies are also reported in the gait literature in young (Grabiner and Troy, 2005) and older adults (Doi et al., 2012). With regard to young adults, if a concurrent task is added to the postural task, the attentional resources allocated to posture will decrease and postural processing will shift toward more automatism. Accordingly, when posture appears more stable under more automatic control conditions in young adults, the concurrent task may serve to improve postural performance. Conversely, the fact that older adults are often unable to maintain their level of postural performance from a single- to a dual-task context supports the second hypothesis stating that they are not able to transfer part of the controlled processing of posture toward more automatic processing and are therefore more exposed to structural interference in terms of shared recruitment of neural structures.

4.4. Prioritization and controlled/automatic ratio

Recently, some studies proposed a conceptual framework of task prioritization wherein the older adults prioritize the postural task (Doumas et al., 2008; Rapp et al., 2006; Simoneau et al., 2008). This framework is based on improved postural DTCs from an easy to a more challenging dual-task design in older adults. We propose two hypotheses linked to a controlled/automatic ratio that could explain this improvement. The first hypothesis is in line with the prioritization framework and proposes that older adults increase the level of controlled processing of posture between the single- and the dual-task condition. However, increasing the level of controlled processing of posture is rather thought to increase postural instability, at least in young adults (e.g., Wulf et al., 2001). Furthermore, the consequence of greater controlled processing of posture should be increased concurrent task DTCs from easy to more challenging tasks which has not been evidenced in the studies proposing the framework of task prioritization (Doumas et al., 2008; Rapp et al., 2006; Simoneau et al., 2008). In sum, this first hypothesis is not supported by the results of the literature. The second hypothesis proposes that increasing the level of difficulty of the postural task re-activates the feasibility of a shift from controlled toward more automatic processing between the single- and the dual-task condition in older adults. This second hypothesis is consistent with the constraint action theory (Wulf and Prinz, 2001). In this model, an improvement of postural stability is associated with a decreased level of controlled processing. The results of Simoneau et al. (2008) clearly corroborated this theory by demonstrating the possibility for older adults to decrease their CoP velocity in a dual-relative to single-task condition while the performance of the concurrent task was not affected. Furthermore, since there is no need for increased cognitive resources allocated to posture, this second hypothesis would explain the absence of increased concurrent task DTC (Doumas et al., 2008; Rapp et al., 2006; Simoneau et al., 2008). The prioritization framework also suggests that young adults prioritize the concurrent task. However, as demonstrated before, this is not strictly speaking a task prioritization as young adults do not really have another choice than to focus on the concurrent task since their posture is processed at the lowest level of control (automatic).

In sum, we propose that stability of posture in single- and dual-task conditions is likely to be ruled by a controlled/automatic ratio that is imposed by the difficulty of the tasks rather than a prioritization framework.

4.5. Potential origins of the age-related increase in controlled processing of posture

In a single-task context, elevated task difficulty levels induce increased activation of cortical structures (Sunaert et al., 2000;

Van Impe et al., 2013). An inability to modulate brain activation as a function of level of difficulty does not appear to explain the present results as it has been shown to be preserved in aging (Goble et al., 2010; Van Impe et al., 2013). However, the necessity for additional recruitment of neural resources in older relative to young adults (Goble et al., 2010; Heuninckx et al., 2005, 2008; Van Impe et al., 2009; Ward and Frackowiak, 2003) likely potentiates the possibility for generic interference. The necessity for this additional recruitment is mainly considered as a compensation for the age-related decline at the peripheral and central levels of functioning. Indeed, at the peripheral level, age-related changes in muscle (Nair, 2005), vestibular (Sloane et al., 1989), joint (Hamerman, 1998) and skin (Bolognia, 1995) systems are well documented. These changes lead to a decreased quantity and/or intensity of the sensory inputs provided by these receptors (Miwa et al., 1995) and an increased sensory noise (Speers et al., 2002), resulting in an altered signal-to-noise ratio. Such alterations at the peripheral level may lead to altered inputs and could result in an increase of the attentional resources required to process the inputs (Boisgontier et al., 2012). At a central level, brain atrophy has already been shown to be associated with decreased postural stability during dual-task walking (Doi et al., 2012). More specifically, age-related changes in the cerebral cortex associated with cell loss, deterioration of grey and/or white matter structures (Giorgio et al., 2010), and damage to the myelin and nerve fibres (Peters, 2002) may affect brain connectivity and result in a decrease of the central processing capacity (Damoiseaux et al., 2008; O'Sullivan et al., 2001). As a consequence, for a specific task (e.g., standing), there is a requirement for increased deployment of attentional resources relative to a maximal capacity. Furthermore, the central weighting of sensory inputs, which is based on the relative reliability of these inputs, has also shown alterations in adult ageing and could therefore also require additional attentional resources (Eikema et al., 2012).

4.6. Controlled versus automatic processing and intermittent versus continuous adjustments of posture

Postural processing requires controlled (cognitive) and automatic components. In this review, we propose that these two types of control should be considered along a continuum that fits with the hierarchical model of Glover (2005). The conceptual framework related to controlled vs. automatic processing is closely associated with the one of intermittent vs. continuous adjustments of movement. Indeed, controlled processing is clearly characterized by sub-movements which are triggered by an error crossing a threshold which defines intermittency (Wolpert et al., 1992) whereas adjustments are performed continuously in the automatic processing mode. A recent study assessing age-related differences in ankle proprioception control of movement supported this continuum idea (Boisgontier and Nougier, 2013) because older adults controlled their movements using more intermittent adjustments as compared to the young adults (as determined by an increased number of sub-movements and weak correlations between peak velocity and constant error). A similar shift in the nature of adjustments may also occur during standing when posture would be more intermittently regulated (more controlled) in older as compared to young adults. This proposition is supported by the stabilogram-diffusion analysis, showing that, over the short term, the steady-state behavior of the CoP movements has a greater tendency to move away from a relative equilibrium point in older relative to young adults (Collins et al., 1995). In other words, the micro-adjustments performed under the continuous (automatic) mode of processing appear less efficient in older adults. Over the longer term, there is an increased probability that movements away from a relative equilibrium point will be offset by corrective adjustments back towards the equilibrium position. In other words, there is an increased probability that errors crossing a certain threshold will be offset by sub-movements which characterise the intermittent (controlled) processing of posture. These age-related differences in processing modes could reflect the required compensation for an altered signal-to-noise ratio (Miwa et al., 1995; Speers et al., 2002) resulting from the deterioration of somatosensory systems (e.g., Bolognia, 1995; Hamerman, 1998; Nair, 2005; Sloane et al., 1989) or from central factors (Giorgio et al., 2010) associated with a less robust perception of postural verticality (Barbieri et al., 2010), thereby requiring larger deviations from the vertical to be detected and subsequently corrected.

4.7. Age-related increases in the cognitive penetrability of postural processing

Cognitive penetrability of postural control is a concept that accounts for the possibility for cognitive processes to influence postural processing (Pylyshyn, 1980). Nevertheless, Stins and Beek (2012) recently proposed the thesis of cognitive impenetrability of postural processing. Their point was based on the fact that the lowest level of postural processing only involves fast automatic adjustments that are therefore immune to cognitive influences, i.e., cognitively impenetrable. The present review demonstrates that, at least in older adults, the lowest level of postural control not only involves automatic but also controlled processing of posture during standing. As a consequence, the content of postural processing in older adults is permanently cognitively penetrable, even at its lowest level of control. This controlled processing of posture is likely to be related to the age-related increase in intermittent adjustments to posture during standing evidenced by Collins et al. (1995). Since age-related increases in intermittent control of movement have also been observed in basic positioning tasks (Boisgontier and Nougier, 2013) this may constitute a generic feature of the aging process that exceeds postural tasks. This latter hypothesis is consistent with imaging studies showing the penetrability of cognition into control of movements (Goble et al., 2010; Heuninckx et al., 2005, 2008; Swinnen et al., 2010) and processing of sensory information (Goble et al., 2011).

5. Conclusion

The present review suggests that older adults are able to manage a postural dual task as well as younger adults in stable standing conditions. However, when complexity of the postural task is increased by dynamic surface and surround conditions, performance on the concurrent task, the postural task, or both is more degraded in older as compared to young adults. These results suggest an age-related increase in the recruitment of generic neural resources indicative of cognitive (controlled) processing of posture during standing associated with greater intermittent adjustments. This cognitive involvement suggests an age-related penetration of cognition into the processing of standing. This begs the question whether it is possible for physically very fit older individuals to overcome or reduce this cognitive penetration and thus behave more according to an automatic processing mode. Moreover, the results reported in this review suggest that the sensitivity of a dual-task design to aging is increased when the challenges imposed by either the manipulation of the support surface condition or both the surface and the visual conditions are increased.

To sum up, a dual-task design should match the following essential requirements: (a) Having at least 4 measures per group is critical: main and concurrent task performance metrics in single and dual tasks; (b) Tasks should be sufficiently difficult in order to reach/exceed the neural resource limits. This requirement is critical to elicit a level of interference that would impact on behavioral performance and make the attentional cost of the main task measurable; (c) The concurrent task should avoid specific interference (involving primary brain areas) because only generic interference (involving association areas) allows making inferences about the intrinsic difficulty in performing the main task; (d) Effects of practice should be controlled. At least this is an important requirement for the concurrent task and this might be left open to the main task where there may be a natural or age-related variation in practice effects, thereby modifying the controlled/automatic ratio.

Author contributions

Conceived and designed review: M.P.B. Performed review: M.P.B. Wrote the paper: M.P.B., I.A.M.B., J.D., A.N., R.T.K., S.P.S.

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