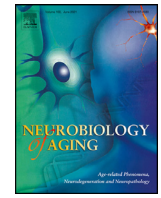
Neurobiology of Aging 105 (2021) 349–364

Contents lists available at ScienceDirect

Neurobiology of Aging

journal homepage: www.elsevier.com/locate/neuaging.org



Review

Brain activity during walking in older adults: Implications for compensatory versus dysfunctional accounts

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A R T I C L E I N F O

Article history:
Received 17 October 2020
Revised 19 May 2021
Accepted 23 May 2021
Available online 31 May 2021

Keywords:
Brain activity
Walking
Aging
Compensation
Dysfunction
Neural control

A B S T R A C T

A prominent trend in the functional brain imaging literature is that older adults exhibit increased brain activity compared to young adults to perform a given task. This phenomenon has been extensively studied for cognitive tasks, with the field converging on interpretations described in two alternative accounts. One account interprets over-activation in older adults as reflecting **neural dysfunction** (increased brain activity – indicates poorer performance), whereas another interprets it as **neural compensation** (increased brain activity - supports better performance). Here we review studies that have recorded brain activity and walking measurements in older adults, and we categorize their findings as reflecting either neural dysfunction or neural compensation. Based on this synthesis, we recommend including multiple task difficulty levels in future work to help differentiate if and when compensation fails as the locomotion task becomes more difficult. Using multiple task difficulty levels with neuroimaging will lead to a more advanced understanding of how age-related changes in locomotor brain activity fit with existing accounts of brain aging and support the development of targeted neural rehabilitation techniques.

1. Introduction

Walking and balance function are major concerns for the aging population. This is a costly problem, with fall related injuries amounting to $50 billion in the U.S in 2015 alone (Florence et al., 2018). Identifying the neural processes that contribute to functional mobility declines with advancing age could lead to new interventions that slow such declines.

Brain functional activity changes with age. Many experiments have revealed that older adults generally recruit additional brain regions compared to young adults when performing a given task (Calautti et al., 2001; V. S. Mattay et al., 2002; Ward & Frackowiak, 2013). Interpretations regarding these age differences are still debated, but it is not known whether the findings from the cognitive neuroscience literature are also applicable to the walking neuroscience literature. Measuring brain activity during walking has many challenges, which we will discuss throughout the paper, but there is a need to take stock of the current state of this research. Moreover, a better understanding of which brain areas, when engaged, are important for walking performance, and which are not, will enable interventions to modify brain activity, or to use activity patterns to predict which individuals may be at risk of future falls or mobility impairment. Furthermore, a greater understanding of interactions with factors such as task demands will aid Interpretations of greater bilaterality of brain activity and patterns of over- and under-activation of brain regions in older adults.

Other reviews have focused on gathering literature with the aim to identify the neural correlates of walking (Hamacher et al., 2015) and neural correlates of dynamic balance (Wittenberg et al., 2017). These reviews contain multiple imaging modalities and tasks, including imagined walking. In general, the reported brain areas active during actual and imagined walking in young healthy adults include prefrontal cortex, premotor area (SMA), basal ganglia, primary motor cortex, and cerebellum. A recent review paper gathered neuroimaging papers in a similar manner to what we have done in this review (Holtzer et al., 2014) with the aim of identi-

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https://doi.org/10.1016/j.neurobiolaging.2021.05.015

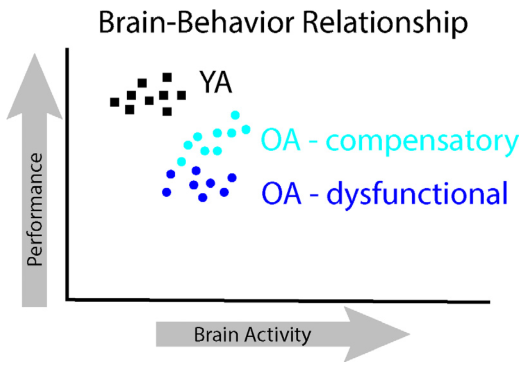

Fig. 1. Illustration of the hypothetical relationship between behavioral performance and brain activity. Younger adults show lower brain activity with higher performance relative to older adults. The older neural compensation group (light blue) shows higher performance than the older dysfunctional group, despite similar levels of brain activity. Moreover, greater brain activity within this group is associated with better performance. This indicates the brain activity in the old compensatory group is beneficial for preserving performance. Performance measures are the basis for categorizing age-related brain over-activation as compensatory or dysfunctional. For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.

fying aging-related differences in the neural correlates of walking. Within this review they mostly conclude that age related mobility decline is associated with the structural integrity of the above mentioned brain regions, and a shift of brain activity to prefrontal areas. In the 7 years since that publication, there have been many more relevant studies published. Here we focus more specifically on brain function, as opposed to structure, and interpreting studies with regard to compensation and dysfunction.

The cognitive literature has suggested (at least) two primary interpretations of over-activation in older adults: neural dysfunction and neural compensation. Fig. 1 depicts hypothetical behavioral performance and brain activity for both young and older adults. Brain-behavior associations allow us to differentiate the older adults who exhibit compensatory brain over-activation (light blue) versus neural dysfunction (dark blue). That is, over-activation is interpreted as compensatory if it is associated with better performance, or dysfunctional if it is associated with poorer performance. We expect older individuals who exhibit neural compensation (*Old Compensatory* group in Fig. 1) to perform relatively well compared to their age-matched peers, but with increased brain activity (relative to young adults) supporting this performance advantage. Alternatively, we would consider brain activity that is not accompanied by preserved performance as reflecting neural dysfunction (dark blue). Furthermore, compensatory over-activation that contributes positively to task performance, may reach a neural resource ceiling, either by increasing activation amplitude in task-appropriate brain regions or by recruiting additional brain regions (Reuter-Lorenz & Cappell, 2008). Such compensation may help—at least in the short term—to overcome age-related brain structural, blood flow, and / or biochemical declines, or even dysfunctional brain activity (Heuninckx et al., 2008; Madden et al., 1999; V. S. Mattay et al., 2002; Reuter-Lorenz et al., 2000).

Dysfunctional over-activation in older adults may result from a number of underlying factors (Koen & Rugg, 2019), including a reduction in specificity of neural representations (Baltes & Lindenberger, 1997; Li & Lindenberger, 2002). Evidence suggests that the functional specialization that characterizes the young adult brain breaks down with aging – this is referred to as dedifferentiation. The ability of a brain area to support its intended task (e.g., the visual cortex processing visual information) generally reduces with age, and regions may become involved for other tasks. Lindenberger & Baltes (1994, 1997) identified that sensory and cognitive performance are more strongly associated with each other in older than young adults, suggesting more shared processing resources, or less specificity of neural processes as age increases. Diffuse biochemical changes may be contributing to global breakdown of neural networks. A computational model of a neural system with reduced dopaminergic modulation reproduced the expected neural noise that accompanies more diffuse brain connectivity (Li et al., 2001; S.C. Li & Lindenberger, 1999). Single-neuron recordings have shown that the visual orientation tuning curve is less selective in older macaque monkeys compared to younger monkeys (Schmolesky et al., 2000). Further, the visual orientation tuning curve has been improved with administration of Gamma Aminobutyric Acid (GABA) agonists (Eysel et al., 1998; Sato et al., 1996), suggesting loss of GABA neurotransmitters contributes to the observed changes in old age (Dustman et al., 1996). This pattern of change is similar to what has been reported with more macro level techniques such as fMRI, although of course fMRI cannot detect single neuron level responses.

Recent research suggests that less segregation of sensorimotor brain networks (Cassady et al., 2019; King et al., 2018) and reduced specificity of motor neural representations (Bernard & Seidler, 2012; Carp et al., 2011) relates to poorer sensorimotor performance among older adults (Bernard & Seidler, 2012; Carp et al., 2011; Cassady et al., 2019; Hausman et al., 2019). Thus, neural dysfunction may contribute to mobility declines with age. The underlying cause of neural dysfunction remains speculative, but possible contributing factors include systemic axon degeneration, loss of synapses, and reduction of neurotransmitter availability and function with advancing age (Cassady et al., 2019; Seidler et al., 2010).

The **compensation** hypothesis suggests that, for a particular level of task demand, additional neural resources are recruited to overcome neural deficits and preserve task performance (Reuter-Lorenz et al., 1999). As age-related declines progress, additional brain resources may be recruited to meet the demands of successful task performance. Since the 1990s, compensation has been used to describe the age-related adaptations that retain function (Bäckman & Dixon, Roger, 1992; Cabeza et al., 1997; Grady et al., 1994, 2000). Often during difficult tasks, compensatory over-activation is observed in prefrontal brain areas and in the contralateral, homologous brain region to that recruited by young adults performing the same task (Cabeza et al., 2004; Reuter-Lorenz et al., 2000). It should be noted that compensation and dysfunction are not mutually exclusive frameworks, as compensation may occur to counteract dysfunction. Furthermore, dysfunctional patterns may emerge as compensatory resource ceilings are reached (Reuter-Lorenz & Cappell, 2008). In other words, studies that have multiple difficulty levels can allow identification of whether brain activity continues to increase with difficulty, or whether a ceiling is reached followed by a decline in performance. Moreover, both compensation and resource limitations can be better evaluated by increasing task difficulty. Gradation also enables stronger interpretation that observed changes in brain activity are indeed a function of the parameter that is being adjusted. Moreover, both compensation and resource limitations can be better evaluated by increasing task difficulty.

In the present review, we synthesize the literature reporting age differences in brain activity and walking performance. In this nascent field, few studies to date have interpreted brain-behavior relationships in the context of existing brain aging accounts. We summarize the research from the past couple of decades where the methodologies and analyses permit such interpretation. We include articles that quantified brain activity during walking tasks with mobile imaging techniques including functional Near Infrared Spectroscopy (fNIRS) and electroencephalog-

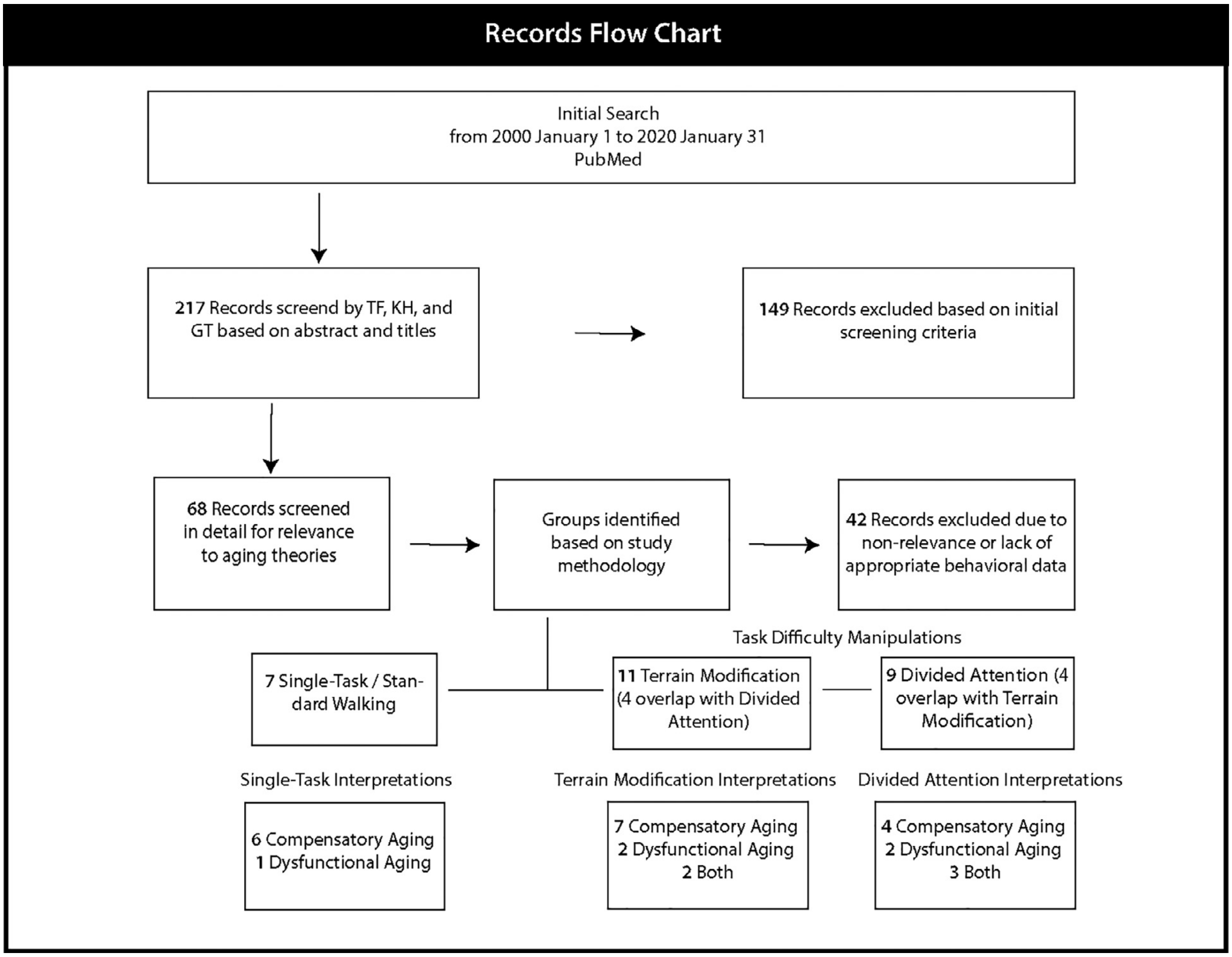

Fig. 2. Diagram displaying the progression of systematic the search results through multiple levels of inclusion and exclusion filtering. We then separated the included articles into three groups (Single Task Walking, Terrain Modification, and Divided Attention Modification) based on their experimental methods and determined whether the results follow compensatory versus dysfunctional patterns.

raphy (EEG), as well as imagined walking performed in the MRI or Positron Emission Tomography (PET) environment as a proxy for physical walking (Jahn et al., 2004, 2008; la Fougère et al., 2010). Of note, many of the included experiments were not designed to explicitly evaluate brain aging theories, although their study design permits such interpretation. We close with suggestions for design and implementation of future studies to facilitate interpretation with respect to compensatory versus dysfunctional accounts.

2. Methodological considerations

We identified articles that (a) recorded functional brain activity during either walking or imagined walking and (b) related brain activity to walking performance. We categorized the articles into those that employed Single-Task Assessments (standard walking) and those that employed Task Difficulty Manipulations (multiple difficulty levels). This organization allows for categorization of low to high motor complexity/difficulty, and a further division of the high difficulty into motor (Terrain Modification) versus motor + cognitive (Divided Attention) difficulty effects. The experiments within the Task Difficulty Manipulation category are subdivided into manipulations of the task of walking itself (Terrain Modifications) and manipulations of the cognitive resources available during the walking task (Divided Attention). This approach to categorization is explained in more detail below.

2.1. Single-task assessments

As illustrated in Fig. 1, brain activity patterns can be linked to the compensation versus dysfunction hypotheses in studies that employ only a single task and assess brain-behavior relationships between old and young adults, or among subgroups of good and poor performing older adults. A single-task assessment can be obtained using mobile brain imaging during walking (e.g fNIRS) or by measuring brain activity separately from walking (e.g. MRI) and comparing it to walking performance. Our original systematic review search did yield single-task experiments that looked at imagined walking during fMRI, however all of these studies were presented in terms of reliability and feasibility, and not necessarily looking for differences in age. Unlike the mobile imaging devices that have higher temporal resolution (fNIRS and EEG), functional MRI has high spatial resolution, but requires participants to lie supine and motionless. Most MRI assessments of mobility have used imagined walking tasks or compared MRI-measured brain activity to walking performance on a separate occasion (e.g., fMRI activity during a cognitive task compared to walking outside of the scanner). We review articles that report using either of these methodologies.

2.2. Task difficulty manipulations

The use of multiple task difficulty levels (e.g., modifying the walking terrain or adding a secondary attention distracting task) can provide insight into potential limits of compensatory processes. Specifically, variations in difficulty can help to determine the point at which evidence of neural dysfunction emerges and a task becomes sufficiently challenging that compensatory reserves are exceeded, or indicate persistent dysfunction across all difficulty levels (Reuter-Lorenz & Cappell, 2008). Past work supports that increasing task difficulty results in increased brain activity within the brain regions recruited by healthy young adults, in addition to other brain areas. For example, Schneider-Garces et al (2010) reported older adults activated bilateral dorsolateral prefrontal cortex (DLPFC) whereas young adults only activated the left DLPFC at the first level of difficulty during a working memory task. For instance, this finding has been demonstrated in several studies in various cognitive domains (Cappell et al., 2010; C. Grady, 2012; Heinzel et al., 2014; Venkata. S. Mattay et al., 2006; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010), with older adults exhibiting proportionally higher activation increases as the load increased compared to young adults (Godde & Voelcker-Rehage, 2010; Hamacher et al., 2015; Meunier et al., 2014). Typically, as a task becomes more difficult, performance will decline. In the next two sections, we describe common methods for increasing the difficulty of walking.

2.2.1. Terrain modifications

Walking terrain impacts mobility (Shumway-Cook et al., 2002). In the lab, terrain can be manipulated by having participants walk on a flat surface and over obstacles (Schulz, 2012). Obstacle navigation is more difficult because the leading foot must be adjusted on approach and landing to avoid tripping or stepping on an obstacle, and foot clearance of both leading and trailing feet must be adjusted during obstacle crossing steps. Furthermore, the gait cycle becomes asymmetrical during obstacle crossing. Using tasks such as obstacle negotiation to increase walking difficulty allows for characterization of how brain activity changes in response to task demands. Therefore, in this review, we included studies that used mobile brain imaging to compare brain activity during normal walking versus tasks with more difficult motor demands such as the presence of obstacles. We refer to these articles as those implementing Terrain Modifications.

2.2.2. Divided attention modifications

Researchers commonly use a secondary task unrelated to walking (e.g., counting backwards by sevens) to increase the difficulty of the locomotion task. A growing body of evidence shows that dual-task costs, defined as the reduction in performance when executing two tasks at the same time, are typically larger in older than young adults (Li et al., 2018; Lövdén et al., 2008). This evidence suggests that older adults allocate more attention to the control of walking than young adults, and older adults place greater priority on walking than on the cognitive task (Brown et al., 2002). Many studies investigating walking with dual-task paradigms use verbal fluency (e.g., reciting alternate letters of the alphabet) or serial subtraction (e.g., counting backwards by threes or sevens) tasks with walking. Dual tasking does not modify the difficulty of walking per se, but rather creates competition for a limited set of resources. We refer to these articles as those implementing Divided Attention Modifications.

2.3. Brain behavior correlations

Our method of categorizing the results of each experiment as supporting compensation or dysfunction is based on assessing the brain-behavior relationships and how the relationships differ between younger and older adults. Moreover, for experiments discussed in the Task Difficulty Manipulation section we examined how brain activity and behavioral outcomes differed under the conditions of lower versus higher task difficulty. This was assessed for both younger and older adults. For example, if brain activity increases more for the older adults, and their performance worsens, compared to younger adults, this would be considered dysfunctional. There is not a consensus on which brain areas are considered "task-relevant" for the control of walking, therefore at this time we define an increase in brain activity and relative increase in behavioral performance as compensatory, and a decrease in behavioral performance as dysfunctional. Additionally, most of the experiments that perform actual walking report anterior-posterior spatiotemporal gait parameters and their variability, including step length, step time, cadence, and gait speed. Variability is typically calculated as the standard deviation of a measure across multiple steps, and is viewed as having negative consequences. Other experiments report muscle activity coherence with EEG signals, or in the event of a visual cueing experiment, correct steps on the cued target. The motor imagery experiments report time to complete the imagined task. Due to the variety of behavioral outcome measures we simplify the results section by stating either "better/improved" or "worse/declined" performance or variability. For additional details about the respective behavioral outcome measures, see Tables 3–5.

3. Literature Search

We searched PubMed with specific criteria. Articles were considered eligible for inclusion if the title and abstract included the search terms listed in Table 1. We did do an initial search in Embase to see if it yielded substantially different results from the PubMed search but it did not. PubMed was the most extensive and similar strategies have been used in the field recently (Holtzer et al, 2014). Articles were excluded prior to the year 2000 because to our knowledge, there are no known relevant studies prior to this date. Articles were included up to the search date, January 31, 2020. Other inclusion / exclusion criteria are provided in Table 2. The search yielded 217 articles. Three authors (TF, KH, GT) performed the initial screening using the inclusion and exclusion criteria in Table 2. We excluded 149 articles based on information contained within the abstracts. We screened the remaining 68 articles in detail to determine their relevance and our potential to interpret the findings using the theories of brain aging. We excluded 41 articles based on lack of group comparisons (i.e., younger versus older adults) or, if the article only included older adults and no difficulty level modulation. Seven papers were included in the Single-Task Assessment category and 20 were in the Task-Difficulty Manipulation category. Within the Task-Difficulty Manipulation category we identified 12 and 8 papers matching the categories of Terrain Modifications and Divided Attention Modifications (3 overlapping between the two), respectively. All articles included in this review are cited in Tables 4, 4, and 5 and bolded in the text for easy identification.

4. Results

4.1. Single-task assessments

The single-task walking category included seven studies that tested associations between brain activity and walking. Four studies measured fluorodeoxyglucose (FDG) uptake via PET after over ground walking (Mitchell et al., 2019; Sakurai et al., 2014, 2017; Shimada et al., 2013). Participants were injected with FDG contrast, performed a walking task, and then completed a PET scan to measure FDG uptake, permitting identification of task-related brain regions. Three studies quantified brain activity during an unrelated

Table 1
Search terms used for identifying the experiments that acquired brain activity during or in relation to mobility related tasks.

Search Terms
Population: "old age" OR "older" OR "elderly" OR "aging" **AND** **Brain Activity:** "fnirs" OR "functional near-infrared spectroscopy" OR "eeg" OR "electroencephalogram" OR "fmri" OR "functional magnetic resonance imaging" OR "pet" OR "positron emission tomography" OR "brain activity" OR "neural activity" **AND** **Behavior:** "balance" OR "walking" OR "gait" OR "mobility" OR "locomotion" OR "imagined walking" **AND** **Year:** AFTER "2000/01/01"

Table 2
Inclusion and exclusion criteria applied to systematic the search.

Inclusion and Exclusion Criteria	
Inclusion	Exclusion
• Studies that compared older and younger adults' brain activity and walking performance. • Studies that measured older adults' brain activity and walking during multiple difficulty levels. • Studies that used some form of mobile brain imaging while participants were walking, turning, obstacle crossing, walking while performing another task (dual-task), etc. • Studies that measured brain activity during imagined walking and related it to a walking or mobility measure acquired outside of the scanner. • Studies that measured brain activity during a stationary acquisition (PET or MRI) and related it to a walking or mobility measure acquired outside of the scanner.	• Studies that were not written in English • Studies that did not present data from healthy older adults. • Studies that present measures of brain structure rather than function. • Studies where the older adult group were also patient populations (PD, MS, diabetes, obesity) • Studies that explored an intervention.

(typically cognitive) task using fMRI and tested associations with walking performance outside of the MRI scanner (Fernandez et al., 2019; Jor'dan et al., 2017; Kawagoe et al., 2015).

Single-Task studies that support compensation: The majority of the studies that evaluated brain activity during walking found an association between increased brain activity and better or sustained performance for the older adults relative to younger adults (Jor'dan et al., 2017; Kawagoe et al., 2015; Mitchell et al., 2019; Sakurai et al., 2014, 2017; Shimada et al., 2013). For example, Mitchell et al. (2019) found similar walking speeds for younger and older adults, but the FDG-PET scan identified increase use of multisensory cortices indicating compensatory brain activity to achieve a similar level of performance. Two studies that acquired brain activity separately from walking also provide support for neural compensation with older age by showing that greater brain activity during the cognitive tasks in the scanner was associated with better walking performance outside the scanner (Jor'dan et al., 2017; Kawagoe et al., 2015). Both studies performed a working memory n-back test during fMRI and assessed whether the brain activity during this task was associated with preferred gait speed and performance on the TUG test, respectively. Jor'dan et al. (2017) reported increased activity across entire networks, whereas Kawagoe et al. (2015) reported positive associations of activation in subcortical regions (i.e. thalamus, putamen, cerebellum) with TUG performance.

Single-Task studies that support dysfunction: Only one out of the seven single-task walking studies supported neural dysfunction with advancing age. Among a cohort of older adults, this study found an association between increased recruitment of parietal-occipital and precuneus regions during the flanker task and higher gait variability outside of the MRI scanner (Fernandez et al. 2019).

In sum, 6 out of 7 articles in Single Task Assessments support that over-activation in older adults serves a compensatory function. That is, higher levels of brain activity corresponded to better walking performance. Conversely, one experiment measuring fMRI during the flanker task revealed over-activation was associated with poorer walking performance, consistent with a dysfunctional pattern.

4.2. Task difficulty manipulations

4.2.1. Terrain modifications

Assessing differences in brain activity across multiple degrees of walking difficulty can help to identify whether or not levels of brain activity increase with increasing difficulty. Multiple difficulty levels also allow assessment of whether the brain activity reaches a ceiling and then either plateaus or declines. By relating brain activity acquired during multiple difficulty levels to task performance, it becomes possible to unpack whether over-activation is compensatory and beneficial at some levels, but less so at others– at very high levels of task difficulty for example. We identified four studies that recorded brain activity while participants negotiated obstacles while walking (Chen et al., 2017; Clark, Rose, et al., 2014; Hawkins et al., 2018; Mirelman et al., 2017). In additional studies, the authors measured brain activity with fNIRS (Spedden et al (2019) used EEG) during simple and complex walking (i.e. auditory or visual cues for stepping) (Clark, Christou, et al., 2014; Spedden et al., 2019; Vitorio et al., 2018). Two experiments assessed imagined walking over obstacles or uneven terrain via fMRI (Allali et al., 2014; Wai et al., 2012). Finally, two studies measured walking over obstacles (Gonzalez-Burgos et al., 2019) and walking with visual cues (Osofundiya et al., 2016) and tested for associations with separately acquired functional brain activity .

Terrain modification studies that support compensation: Four articles that measured brain activity during a modified terrain walking task support an interpretation of neural compensation (Clark, Christou, et al., 2014; Clark, Rose, et al., 2014; Spedden et al., 2019; Vitorio et al., 2018). That is, greater brain activity in the PFC was associated with better walking performance for older adults. Studies that measured brain activity during imag-

Table 3
Single Task Assessments.

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Fernandez et al., 2019)	YoungerAdults: $n = 21$, 100% F, 21 ± 2.5 y Older Adults: = 34, 100% F, 72 ± 5.3 y	fMRI	1)Flanker task 2) TUG 3) SPPB 4) Gait analysis	Behavior: OAs had lower accuracy in the flanker, with a higher accuracy cost, and slower reaction time compared to YAs. Brain: OAs & YAs greater recruitment within the fronto-parietal-occipital network during the incongruent distractors on the flanker task. OAs had increased activation in dorsal parieto-occipitial sulcus and precuneus areas relative to YA's. Brain-Behavior Associations: Increased recruitment of left dorsal parieto-occipital sulcus and precuneus associated with higher gait variability.	Dysfunction: Increased recruitment of parietal-occipital and precuneus areas associated with higher gait variability in older adults.
(Jor'dan et al., 2017)	Older Adults: $n = 27$, 74% F, 70+ y	fMRI	1) N-back 2) TCD ultrasound 3) Preferred pace walking	Brain-Behavior Associations: Activation in dorsal attention network and executive networks were associated with task-related brain activity changes and walking speed.	Compensation: Greater activation with better n-back performance and also associated with faster gait speed.
(Kawagoe et al., 2015)	Older Adults: $n = 32$, 37.5% F, 73.06 ± 4.83 y	fMRI	1) TUG 2) 10m walk 3) Nback test	Brain: Increased brain activity as nback difficulty increased. Brain-Behavior Associations: Thalamus, putamen, and cerebellum activation during nback task positively associated with TUG performance.	Compensation: OAs who had increased activity in subcortical regions performed better on mobility tasks.
(Mitchell et al., 2019)	Younger Adults: $n = 7$, 4 F, 24± 3 y Older Adults: $n = 7$, 3 F, 59 ± 2 y	FDG-PET	1) Gait speed	Behavioral: Similar walking performance (i.e. gait speed) between OA's and YA's. Brain: OAs had increased precentral and fusiform gyri, reduced deactivation of multisensory cortices (inferior frontal, postcentral, and fusiform gyri), and reduced activation of the middle frontal gyrus and cuneus	Compensation: OAs increase the use of the multisensory cortices and frontal brain regions compared to YAs, likely in order to maintain similar walking performance.
(Sakurai et al., 2014)	Older Adults: $n = 182$, 100% F, 69.4 ± 6.6 y	FDG-PET	1) Gait speed 2) Step length 3) Step frequency	Brain-Behavior Associations: Slower max gait speed was associated with lower normalized-rCMRglc in prefrontal, posterior cingulate and parietal cortices.	Dysfunction: Those that had worse gait performance had impaired uptake of FDG, thus the responsible regions were inefficiently accessing necessary resources to maintain performance
(Sakurai et al., 2017)	Older Adults: $n = 149$, 100% F, 70.1± 6.2 y	FDG-PET	1) Gait speed 2) Step length 3) Cadence during preferred and fast walking	Brain-Behavior Associations: Slower gait speed and lower cadenceassociated with lower activity in posterior cingulate, primary sensorimotor, occipital, and parietal cortices.	Compensation: OAs that reduced activity in these key neural control areas suffered from diminished mobility performance, which means those that activate areas will improve performance.
(Shimada et al., 2013)	Older Adults: $n = 24$,100% F, 78 ± 2.3 y	FDG-PET	1) Step length variability	Brain-Behavior Associations: Greater step length variation associated with deactivation of SMA and DLPFC.	Dysfunction: Those that had the greater step length variability were less able to access the essential neural resources

Key: F, female; M, male; OA, Older Adults; PFC, prefrontal cortex; rCMRglc, regional cerebral metabolic rate of glucose consumption; SMA, supplementary motor area; SPPB, short physical performance battery; YA, Younger Adults.

ined walking over obstacles and uneven terrain also reported compensatory brain activity patterns (Allali et al., 2014; Wai et al., 2012). Greater activation in supplementary motor area, dorsolateral frontal, and frontoparietal regions was associated with better performance of imagined walking over obstacles (i.e. shorter time to complete the imagined walking course) and uneven terrain. Additionally, one of the two articles that tested for associations with separately acquired functional brain activity also provides support that over-activation in older adults is compensatory (Gonzalez-Burgos et al. 2019). Specifically, Gonzalez-Burgos et al. (2019) had participants complete a Simon and Stroop task in the fMRI scanner and identified brain regions that associated with gait speed while walking over obstacles. The authors found increased bilateral precuneus activation was related to faster gait speed, both overground and over obstacles.

Terrain modification studies that support dysfunction: Two studies that reported brain activity acquired via fNIRS during obstacle crossing (Hawkins et al. 2018) or cued walking (Osofundiya et al. 2016) found an association between increased brain activity in PFC and poorer performance, suggesting neural dysfunction. More specifically, Hawkins et al. (2018) showed a steeper drop in gait speed over obstacles for older compared to younger adults and Osofundiya et al. (2016) found a relationship between increased PFC and slower walking speed within the older adult group, in the presence of the cues.

Terrain modification studies with ambiguous classification: Two experiments included an obstacle avoidance task that could be interpreted to support either compensation or dysfunction. Mirelman et al. (2017) showed greater PFC activation for older compared to younger adults, but did not find significant perfor-

Table 4
Task difficulty manipulation: terrain modification.

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Allali et al., 2014)	Younger Adults: $n = 14$; 71% F; 27.0 ± 3.6 y Older Adults: $n = 14$; 71% F; 66.0 ± 3.5 y	fMRI	Motor imagery of gait + control imagery task (visual imagery task); varied task complexity. Also performed Stroop task.	Behavioral: Older adults did not show change in performance (time to complete walking path) based on complexity. Brain: YA and OA recruited network of motor, frontal, & cerebellar regions during gait imagery task. Age-related increase in brain activity during gait imagery in several regions: right SMA, right orbitofrontal cortex, and left dorsolateral frontal cortex. Activity in the left hippocampus was related to task complexity in OAs only.	Compensation: Activation in non-task specific regions is a compensatory recruitment for the inability to perform the cobblestone imagery properly (did not show a task complexity interaction, i.e. longer time).
(Chen et al., 2017)[a]	Older Adults: $n = 90$; 57% F; 78.1 ± 5.5 years	fNIRS	Normal pace walk and obstacle negotiation (gait speed). Obstacle negotiation was red shapes on ground to avoid.	Behavioral: Gait speed was slower during Obstacle Negotiation (ON) compared to Normal Walking (NW). Slow walkers had less of a decrease in speed from NW to ON compared to fast walkers. Brain: Increased PFC activation in ON condition compared to NW. Brain Behavior Associations: Slow walking moderated brain activity increase from NW to ON, while people with slow gait had higher activity during NW compared to fast walkers.	Compensation: The slow group had smaller obstacle costs (velocity) compared to normal, with greater PFC activation. Dysfunction: The slow group was slower across all conditions, which could be indicative of dysfunctional activation.
(Clark, Christou, et al., 2014)	Older Adults: $n = 14$*; sex not reported*; 77.1 ± 5.56 y	fNIRS	Treadmill walking and overground walking–wearing normal shoes, wearing textured insoles, and wearing no shoes.	Brain: Textured insoles (increased somatosensory input) resulted in reduced prefrontal activity in both hemispheres for both treadmill and overground walking. No shoes (increased somatosensory input) resulted in reduced prefrontal activity in both hemispheres for treadmill walking only.	Compensation: Increased proprioception (textured insoles) decreases prefrontal activity possibly indicating prefrontal activation is inherently meant to compensate for diminished proprioception at the sensor level.
(Clark, Rose, et al., 2014)[a]	Older Adults: $n = 16$; 50% F; 77.2 ± 5.6 y	fNIRS	Participants walked at preferred speed (control task) + walked on the same course under different challenging conditions: carrying a tray, negotiating obstacles, and wearing a weighted vest.	Brain: Higher prefrontal activity + higher skin conductance level during the preparation phase of complex walking tasks relative to the control task. This elevation of prefrontal activity remained during performance of the complex tasks. Brain-Behavior Associations: Larger increase in prefrontal activity was found to be linked to "better" gait during complex walking tasks	Compensation: Increased prefrontal activity was linked to better performance during the complex walking tasks.
(Gonzalez et al., 2019)	Older Adults: $n = 20$, 55% F, 63-80 years	fMRI	Brain activity was assessed before and during a spatial Simon and Stroop task. Brain activity change was correlated with gait speed during normal speed walking, fast walking, and walking over obstacles.	Brain-Behavior Associations: Brain activity change associated with preferred gait pace, particularly bilateral precuneus changes with fast pace gait, fast walking over obstacles, and 400m walk time. Brain activity change in L mid frontal gyrus during spatial task associated with preferred gait.	Compensation: OAs that performed better (faster walk speed) had increased brain activity changes.
(Hawkins et al., 2018)	Younger Adults: $n = 9$; 56% F; 22.4 ± 3.21 y Older Adults: $n = 15$; 53% F; 77.2 ± 5.6 y	fNIRS	Three walking difficulties, typical walking, over obstacles	Behavioral: Older adults had an increased obstacle cost (slower speed) Brain: Significant increase in PFC activity during typical and obstacles for OA, increases in complexity=increase in activation for OAs and decrease in walking speed as complexity increased. Brain-Behavior Associations: Increased PFC activation accompanied by a steep drop in walking speed with introduction of obstacles.	Dysfunction: The authors argue the increased PFC is compensatory, but because increased PFC was accompanied with a steep drop in walking speed we classify this as dysfunctional activation.

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Table 4 (*continued*)

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Mirelman et al., 2017)[a]	Younger Adults: $n = 23$; 57% F; 30.9 ± 3.7 y Older Adults: $n = 20$; 50% F; 69.7 ± 5.8 y	fNIRS	Gait speed, stride length and stride length variability during usual walking and obstacle negotiation	Behavioral: Older adults typically had worse gait measures (more variable). Brain: Old adults increase PFC brain activity in normal walking compared to standing whereas younger do not. Both younger and old adults increase brain activity in the obstacle negotiation compared to standing, but older adults increase more. Brain-Behavior Associations: Increased PFC activation associated with increased variability in the older adults.	Compensation: Older adults increase activation in the presence of obstacles compared to younger adults. Arguably required to compensate for lack of automaticity. Dysfunction: Increased activation was associated with gait variability, which could indicate inefficiency.
(Osofundiya et al., 2016)[a]	Older Adults: $n = 10$; 80% F; 80.6 ± 7.5 y	fNIRS	Visually-guided walking	Behavioral: ~30–40% slower gait speeds when compared to the simple walking task. Brain: Complex ambulatory tasks were associated with ~2–3.5 times greater PFC oxygenation levels.	Dysfunction: The drastic drop in gait speed with the precision walking and increased PFC oxygenation suggests dysfunction.
(Spedden et al., 2019)	Younger Adults: $n = 15$; 53%; 22.1± 1.7 y Older Adults: $n = 15$; 53% F; 68.3 ± 2.7 y	EEG	Visually guided (VG) walking versus normal walking	Behavioral: Older adults typically had decreased performance (number of targets hit) compared to younger. Brain: Intramuscular coherence was lower in older people compared to younger participants during both tasks. In addition, coherence was generally greater during VG than during normal walking across age groups. Brain-Behavior Associations: Performance on the VG task was associated with task-related corticomuscular coherence modulations within the older group.	Compensation: Older individuals that increased coherence during the VG task increased performance, which is an argument for compensation.
(Vitorio et al., 2018)	Younger Adults: $n = 17$; 53% F; 20.3 ± 1.2 y Older Adults: $n = 18$; 50% F; 72.6 ± 8.0 years	fNIRS	Walked on a motorized treadmill for 5 min (5 trials with alternating 30-sec blocks of usual walking and Rhythmic Auditory Cueing (RAC) walking)	Behavioral: Gait variability (step length and step velocity) decreased during cued walking relative to usual walking. Brain: Prefrontal HbO_2 levels increased during cued walking relative to usual walking. Older adults showed greater HbO_2 levels in multiple motor regions during cued walking although the response reduced with repeated exposure. Brain-Behavior Associations: In older adults, lower depression scores, higher cognitive functioning, and reduced gait variability were linked with increased HbO_2 levels during RAC walking.	Compensation: Improved performance was associated with higher PFC HbO_2 levels indicating compensation.
(Wai et al., 2012)	Young Adults: $n = 14$; 50% F; 21.5 ± 1.6 y Older Adults: $n = 13$; 46% F; 64.8 ± 6.1 y	fMRI	Video clip of gait initiation, stepping over an obstacle and gait termination	Brain: An extensive network of bilateral SMA, PMd, posterior parietal lobe and visual association areas was activated in the old versus the younger participants. Increased activation in bilateral pre-SMA, PMd, ventral premotor area, precentral, posterior parietal lobes and visual association areas were activated in the old when compared to the younger.	Compensation: The visual areas were activated to a greater extent throughout the progression of the task (YA<OA). Increased reliance on visual areas is compensatory activation.

Key F, female; M, male; OA, Older Adults; PFC, prefrontal cortex; PMd, dorsal premotor; SMA, supplementary motor area; YA, Younger Adults

[a] Denotes paper that is also included in the Task Difficulty Manipulation: Divided Attention category. In this table, we discuss only the results relevant to the gait-task modulation.

Table 5
Task difficulty manipulation: divided attention.

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Beurskens et al., 2014)	Young Adults: n = 15; sex not reported; 24.5 ± 3.3 y Older Adults: n = 10; sex not reported; 71.0 ± 3.8 y	fNIRS (average prefrontal HbO_2)	1) TW 2) Alpha 3) Check 3) TW + Alpha 4) TW + Check	Behavioral: OAs performed worse than YAs on the secondary tasks (i.e., Alpha and Check). Step duration increased with increasing task complexity for OAs. Greater dual task cost for some gait measures for OAs compared to YAs (e.g., step length shortened more and and step duration lengthened more for OAs than YAs during TW+Check and TW+Alpha). Brain Activity, YAs: Little activity changes for prefrontal cortex from single to dual task for both dual task conditions. Brain Activity, OAs: Substantial decrease in prefrontal activity for OAs during the most difficult task (TW+Check).	Compensation: Brain activity maintained at a similar level between TW and the easier dual task (TW+Alpha). However, for OAs but not YAs, brain activity decreased with increasing task demand, as seen at the most difficult level of the task, the TW+Check task. This could indicate that, during the most difficult task, the OAs reached their resource ceiling. Thus, the decreased prefrontal activity could represent a shift in processing from frontal regions to alternative brain networks, to still allow for performance of the dual task.
(Chen et al., 2017)[a]	Older Adults: n = 90; 51% F 78.1 ± 5.5 y	fNIRS (average prefrontal HbO_2)	1) NW 2) WWT 3) ON 4) WWT+ON	Behavioral: Reduced gait speed during WWT, ON, and WWT+ON. Brain Activity: Increased prefrontal activity during WWT compared to NW and WWT+ON compared to ON. Brain- Behavior Associations: Compared to those with normal gait speed, those with slow gait had smaller reductions in gait speed paired with greater activity during ON+WWT.	Compensation: The increased prefrontal activity seen with increased task complexity suggests compensation. Also, those with slower gait had smaller reductions in gait speed paired and greater prefrontal activity during more challenging conditions, again suggesting compensation. Dysfunction: Those with slow gait walked slower across all task conditions, which could suggest neural dysfunction.
(Clark, Rose, et al., 2014)[a]	Older Adults: *n* = 16; 50% F; 77.2 ± 5.6 y	fNIRS	Participants walked at preferred speed (control task) + walked while talking (WWT).	Brain: Higher prefrontal activity + higher skin conductance level during the preparation phase of complex walking tasks relative to the control task. This elevation of prefrontal activity remained during performance of the complex tasks. Brain-Behavior Associations: Larger increase in prefrontal activity was found to be linked to "better" gait during complex walking tasks	Compensation: Increased prefrontal activity was linked to better performance during the complex walking tasks.
(Holtzer et al., 2015)	Older Adults: n = 348; 59% F 76.8 ± 6.8 y	fNIRS (average prefrontal HbO_2)	1) NW 2) Alpha 3) WWT	Behavioral: Reduced stride length and gait speed during WWT versus NW. Brain Activity: Increased brain activity for WWT versus NW. Elevated activity was sustained throughout the entire WWT trial. Brain-Behavior Associations: During WWT, higher activity related to increased stride length and better cognitive performance. Neither NW nor WWT activity related to gait speed.	Compensation: Greater activity during WWT suggests compensation (i.e., increased brain activity to adjust for greater task complexity level). Increased brain activity maintained throughout the entire trial suggests that more brain resources are necessary for supporting cognitively-demanding walking (rather than needed only to adapt to the task at the start). The relationship between increased activity and better gait (increased stride length) and better cognitive performance during WWT further suggests compensation.

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Table 5 (*continued*)

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Holtzer et al., 2016)[b]	Older Adults: n = 167; 51% F; 74.4 ± 6.0 y	fNIRS (average prefrontal HbO_2)	1) NW 2) Alpha 3) WWT	Behavioral: Slower gait speed during WWT versus NW. Similar rate of correct letters, but higher error rate in WWT versus Alpha. Brain Activity: Increased brain activity from NW to Alpha to WWT. Brain-Behavior Associations: Higher levels of activity during WWT related to better cognitive performance, but slower gait velocity.	Compensation: Increased prefrontal activity from NW to Alpha to WWT suggests that greater brain activity is needed to support performance of the cognitive task, especially while walking. Individuals generated correct letters at a similar rate during WWT compared to Alpha, supporting that this is compensatory over-activity. Dysfunction: Increased brain activity did not support maintenance of gait speed during WWT compared to NW, suggesting that the over-activity was not efficient for maintaining gait performance.
(Holtzer et al., 2019)	No Self- Reported Fear of Falling (FOF): n = 56; 45% F; 76.7 ± 6.4 y Self-Reported Fear of Falling (FOF): n = 19; 68% F; 79.8 ± 6.0 y	fNIRS (average prefrontal HbO_2)	1) NW 2) Alpha 3) WWT (3 trials of each condition)	Behavioral: FOF associated with slower stride velocity. Stride velocity slowed from NW to WWT. Across the three trials of each condition, participants increased stride velocity and rate of correct letter generation. Brain Activity, No FOF: Increased brain activity from NW to WWT. activity decreased over repeated trials for WWT and Alpha. Brain Activity, FOF: Increased brain activity from NW to WWT. activity decreased over repeated trials for WWT and Alpha. Comparison of No FOF to FOF: Increased brain activity during WWT for the FOF group compared to the no FOF group. Brain activity increased more from NW to WWT for the FOF group. FOF group saw less decline in activity from the first to the second WWT trials.	Compensation, no FOF: Prefrontal activity increased from NW to WWT to compensate for the more challenging task. Further, activity decreased over repeated trials; less brain activity was needed to support improved gait and cognitive performance over repeated trials. Neural Dysfunction, FOF: Greater increases in brain activity from NW to WWT and Alpha to WWT for the FOF group suggests dysfunction. The FOF group required more brain activity to support the dual task and they performed worse (i.e., they walked slower) than the no FOF group. Less declines in prefrontal activity from the first to second WWT trials for the FOF group also suggests less improvement in neural efficiency for these groups with repeated exposure to a task.
(Mirelman et al., 2017)[a]	Young Adults: n = 23; 57% F; 30.9 ± 3.7 y Older Adults: n = 20; 50% F; 69.7 ± 5.8 y	fNIRS (average prefrontal HbO_2)	1) Standing 2) NW 3) WWS	Behavioral: Compared to YAs, OAs performed worse on gait measures (i.e., shorter stride length and slower gait speed). YAs and OAs had similar scores on the subtraction tasks. Brain Activity, YAs vs. OAs: OAs had higher levels of prefrontal activity compared to YAs across all walking conditions. Both groups had similar increases in prefrontal activity from NW to WWS. Brain-Behavior Associations: Greater prefrontal activity associated with increased gait variability during NW and WWS for OAs but not for YAs.	Compensation: All participants recruited more neural resources to perform the more difficult tasks, suggesting that this increased activation is compensatory. Further, as a compensatory mechanism, OAs required greater prefrontal activity to perform each of the tasks compared to YAs, even for the simplest condition (NW). This increased activation allowed OAs to perform the NW and WWS tasks at similar proficiency compared to the YAs (e.g., similar gait variability). Neural Dysfunction: Increased prefrontal activity during NW and WWS associated with increased gait variability. This could represent neural dysfunction in that increased brain activity was not sufficient to maintain performance in either condition.

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Table 5 (*continued*)

Citation	Participants	Imaging techniques	Behavioral measures	Primary results	Aging theory
(Osofundiya et al., 2016)[a]	Older Adults: n = 10; 80% F; 80.6 ± 7.5 y	fNIRS (average prefrontal HbO_2)	1) NW 2) WWT	Behavioral: Participants walked 30-40% slower during WWT compared to NW. Brain Activity: WWT associated with 2–3.5x greater prefrontal activity compared to NW.	Neural Dysfunction: Greater prefrontal activity but substantially slower gait speed during WWT compared to NW suggests neural dysfunction. The greater recruitment of frontal brain resources during WWT did not allow participants to maintain the same level of behavioral performance.
(Stuart et al., 2019)	Young Adults: n = 17; 53% F; 20.3 ± 1.2 y Older Adults: n = 18; 50% F; 72.6 ± 8.0 y	fNIRS (multiple ROIs examined separately, left and right: prefrontal cortex, M1, SMA, and PMC)	1) TW 2) DV 3) TW + DV	Behavioral: No change in gait performance between TW and TW+DV. Brain Activity: Brain activity increased during TW + DV in PMC, SMA, and M1, but not in prefrontal cortex. There were few group differences between YAs and OAs during TW+DV. The only differences were in left SMA. OAs did not increase left SMA activity to the same extent as YAs during TW+DV. Brain-Behavior Associations: There were no associations between brain activity in any of the ROIs and gait measures. The only consistent relationship was between greater activity in most ROIs during TW+DV and better executive function performance (measured using separate cognitive tasks). Effect of Repeated Trials: Brain activity increased in response to TW+DV primarily with the first task exposure (i.e., Trials 1 and/or 2 of 5). The response attenuated with subsequent trials.	Compensation: Increased brain activity with increasing task complexity but no declines in gait performance suggests compensation. The association between better executive function and greater activity during the dual task suggests that those with better executive function have a greater capacity to increase activity as a compensatory measure.

Key. F, female; FOF, fear of falling; HbO_2 , cortical oxygenated haemoglobin; M1, primary motor cortex; M, male; OA, older adult; PMC, premotor cortex; ROI, region of interest; SMA, supplementary motor area; YA, younger adult; NW, normal walk; TW, treadmill walking; Alpha, alphabet (i.e., reciting alternate letters of the alphabet); Check, checking boxes on a sheet of paper; TW+Alpha, treadmill walking concurrently with alphabet task; TW+Check, treadmill walking concurrently with checking task; WWT, walking while talking (i.e., while completing the Alpha task); WWS, walking while subtracting (e.g., performing serial subtractions by 3s); ON, obstacle negotiation; ON+WWT, obstacle negotiation during the walking while talking task; DV, digit vigilance (i.e., counting how many times a given number was played on an audio recording); TW+DV, treadmill walking concurrently with the digit vigilance task

[a] Denotes paper that is also included in the Task Difficulty Manipulation: Terrain Modification category. In this table, we discuss only the results relevant to divided attention. In Table 2, we discuss the results relevant to the modification of gait task complexity.

[b] In addition to healthy older adults, this study also included individuals with peripheral and neurologic gait abnormalities. Here we report only the demographics, results, and aging theory conclusions relevant to the healthy older adults included in this study.

mance decrements during obstacle crossing. This suggests that the identified higher levels of PFC activity served a compensatory function in older adults. However, the authors also reported an association between increased PFC activity and greater gait variability (often associated with balance difficulties (Hausdorff et al., 2001)). This suggests that increased PFC activity could also reflect neural dysfunction that underlies greater gait variability. Chen et al. (2017) introduced flat red areas on the ground (i.e., obstacles) for participants to avoid and reported increased PFC activity during obstacle walking compared to normal walking in older adults. They also found that slow compared to fast walkers showed both increased PFC activation and smaller reductions in gait speed during obstacle walking compared to fast walkers, suggestive of compensation. However, an alternative argument points to neural dysfunction, as the already diminished performance in the slow group might limit the additional cost of the obstacles.

Seven of the eleven articles in this category support that over-activation in older adults is compensatory for locomotion. Two articles present findings that are consistent with neural dysfunction, and an additional two reported data that could be interpreted as supporting either neural dysfunction or compensation. Thus, the majority of articles in the Terrain Modification category support compensation. However, importantly, no experimental design included multiple levels of terrain modification, which would have permitted investigation of whether neural compensation reaches a ceiling.

4.2.2. Divided attention modifications

Each of the studies in this category used fNIRs to measure PFC brain activity during single and dual task walking. Dual task walking involved secondary tasks to divide attention. Secondary tasks included reciting alternate letters of the alphabet, checking boxes on a paper, walking while talking, and walking while subtracting by sevens.

Divided attention studies that support compensation: Four studies provided evidence that increased PFC activity during dual task walking, compared to normal walking, relates to better walking performance (Beurskens et al., 2014; Clark, Rose, et al., 2014; Holtzer et al., 2015; Stuart et al., 2019). Overall, these findings suggest PFC activity during cognitively demanding walking in older age.

Divided attention studies that support dysfunction: In a cohort of older adults, Osofundiya et al. (2016) found that gait speed slowed by about 30% –40% and PFC activity increased by 2–3.5 times as task complexity increased (normal walking vs. dual-task walking). This could be attributed to neural dysfunction, as greater PFC activity was associated with slower gait speeds in the more complex task conditions. Mirelman et al., (2017) revealed increased PFC activity for older versus younger adults when walking while talking versus walking alone compared to younger adults. This study also found greater gait variability during walking while talking in older adults relative to younger adults, suggesting that this identified increased PFC activity reflects neural dysfunction.

Divided attention studies with ambiguous classification: Chen et al., (2017) found that participants with a smaller reduction in gait speed from standard walking to walking while talking showed greater PFC activity as task complexity increased. However, those older adults who walked slower across all task conditions also showed greater increases in PFC activity as task difficulty increased. Potentially, these individuals were recruiting more neural resources, but not performing better than their peers who walked faster. Holtzer et al., (2016) found that greater PFC activity during dual task walking associated with better performance on the secondary cognitive task (reciting alternate letters of the alphabet), which could be interpreted as neural compensation. However, increased brain activity was not associated with gait speed during the dual task walking, suggesting that over-activation reflects neural dysfunction. Holtzer et al., (2019) found that PFC activity decreases with practice of dual-task walking for older adults, regardless of self-reported fear of falling. This indicates that initially older adults may increase PFC activity to maintain performance; then, as learning progresses, fewer cognitive resources are required. However, those who reported a fear of falling had greater increases in PFC activity from normal walking to dual task walking. These individuals also showed less decrease in PFC activity through repeated trials, suggesting dysfunctional brain activity patterns.

In summary, three articles in the Divided Attention category support compensation, two articles support dysfunction, and an additional three provide evidence for both compensation and neural dysfunction in older adults. Thus, compared to the other categories, the Divided Attention articles provide weaker support for the notion that over-activation in older adults reflects compensation. However, it should be noted that the different secondary tasks employed by the experiments may also contribute to the variability in outcomes.

5. Discussion

In the present review we aimed to (1) identify recent studies combining neuroimaging and measurement of mobility; and (2) interpret these findings in the context of two key cognitive brain-aging theories. Recent technological advancements have enabled the combination of mobility and neuroimaging studies. We reviewed publications from the past two decades that involved neuroimaging and mobility measurements in older adults. We interpreted the findings in the context of two of the most common brain-aging hypotheses posited to explain over-activation in older relative to younger adults: neural dysfunction and neural compensation. We organized the studies into three main categories based on methodology, (1) Single Task Assessment; (2) Task Difficulty Manipulation: Terrain Modification; and (3) Task Difficulty Manipulation: Divided Attention Modifications. Only a few of these experiments originally intended to interpret their findings in the context of the brain-aging theories. Thus, our review provides novel re-interpretation of existing data and we gain an understanding about how methodological considerations and outcome variables can influence interpretations in the context of brain aging.

Seventeen out of twenty-seven experiments found that older adults exhibit compensatory patterns of brain activity. Five report patterns of dysfunctional brain activity and the final five have ambiguous interpretations. The overall pattern was as follows: Single Task (6 compensatory, 1 dysfunctional), Terrain Modification (7 compensatory, 2 dysfunctional, 2 both), and Divided Attention (4 compensatory, 2 dysfunctional, 3 both). One way to understand the distribution of findings is in terms of the level of difficulty posed by the differing methodologies. According to a compensation framework (Reuter-Lorenz & Cappell, 2008), when the demand is too great, resources may be insufficient to achieve adequate compensation (i.e. a resource ceiling). It follows that effective compensation will be more evident for easier to mid-range tasks, and less evident or successful as difficulty increases. It is likely the single task assessments are in a lower difficulty range for a generally healthy older adult population, but nonetheless they require increased brain activity for older adults to perform at similar levels to the younger adults. The Terrain Modification methodologies vary, but most provide some form of obstacle to avoid, which increases task difficulty. For some participants, this may be enough to reach a ceiling of compensatory brain activation, hence a greater number of interpretations of dysfunction compared to the single task. Divided Attention has the greatest spread of result interpretations. Following the logic above, this reflects a greater number of people have reached their neural resource ceiling in these paradigms.

Within the Single Task category, all of the included experiments were either task-based fMRI or FDG-PET correlated with walking performance outside of the scanner. The advantage with these forms of brain activity acquisition is that we can measure brain activity anywhere throughout the brain. However, many of these experiments focused on regions or networks of interest due to specific hypotheses about particular brain regions or whole brain networks, making it difficult to determine whether there are shared task-relevant or compensatory brain regions. Regardless of where the area was, if activation occurred in conjunction with improved performance, we classified this as compensatory. In the Terrain Modification category, 7 used fNIRS, which was limited to acquiring brain activity signal from the prefrontal cortex. Three studies used fMRI (imagined walking) and 1 used EEG (coherence of brain signal to muscle activity). All studies in the divided attention task used fNIRS. Future work will seek to uncover specifically which brain areas healthy younger adults use during these tasks and which brain areas older adults may be recruiting to compensate. This is critical to informing future targeted neural stimulation paradigms.

5.1. Limitations

There are several limitations to this review and the experiments on which it is based:

1) In this review we have operationalized the terms compensation and dysfunction as distinct outcomes, suggesting that an individual person either presents with compensation or dysfunction. However, it is possible that someone would not fit either outcome. For example, an older adult could present with increased brain activity (relative to a younger adult) and show little improvement in performance, which may indicate this person is a "maintainer" (Cabeza et al., 2018). In this case, compensation may be helping to counteract dysfunction in that individual. With many studies only reporting differences in brain activity and performance at a single difficulty level, there is limited information, and therefore speculative to assign a specific label to their brain-behavior relationship. Therefore, our overarching recommendation for improving the ability to decipher brain-behavior relationships is to incorporate experimental designs with multiple difficulty levels (see Section 5.2).
2) The interpretation of the studies' results in the context of the two conceptual accounts (compensation vs. dysfunction) is rather subjective. First, there are a variety of behavioral measures that are used, and it is not certain whether performance on one metric translates to another. Second, in the case in which an article's results support dysfunction, we don't know whether older adult walking performance would be even worse without the observed over-activation. One way to tease this apart in future studies is to implement multiple levels of task difficulty. This is discussed in more detail in section 5.2 below.
3) The majority of the studies quantified brain activity with fNIRS, which limited measurements to only PFC recordings. This provides an incomplete picture of how brain activity subserves task performance. For instance, while dual task walking could associate with increased PFC activation in aging, it could also associate with decreased activation in other brain regions (e.g., primary motor cortex). That is, with aging, some brain regions could show evidence of compensation in response to a more demanding task, while other brain regions could show evidence suggesting neural dysfunction or other patterns. Similarly, imagined walking may have similar limitations in that brain regions that are typically active during actual walking, may not be active during imagined walking, therefore not providing a complete picture of how brain activity subserves the task of interest.
4) The divided attention paradigms use a variety of secondary tasks (i.e. verbal fluency, serial subtraction, etc.), which may recruit different brain regions from each other. Further, these secondary tasks may not recruit similar brain regions as the primary walking task. These issues likely lead to variability in study outcomes. Additionally, the brain activity during the cognitive task alone is often ignored (i.e., dual task costs of activation for the cognitive task are typically not presented), and should be considered in future divided attention paradigms.
5) There is not a standard reference for determining interparticipant change in brain activity with varying difficulty conditions. Previous studies have used static baseline conditions of standing (Fraser et al., 2016; Holtzer et al., 2011; Mirelman et al., 2017) or sitting (Beurskens et al., 2014), which may have inflated findings. Indeed, when using standing as a baseline condition, it is unsurprising to find large increases in brain activity levels across all regions when younger and older adults perform a motor task (i.e. walking), with greater response in PFC and primary motor cortex for older adults. Therefore, a static baseline comparison may not be appropriate and could explain previous significant PFC activity changes.
6) Most of the studies presented did not account for structural brain changes with age. Arguably, one of the most important missing components in many of these studies is a measure and characterization of structural integrity (Melie-Garcia et al., 2018). Even with healthy aging, total brain volume diminishes about 0.2% –0.5% per year starting at age 35 (Hedman et al., 2012). This is a major consideration for determining whether brain activation is associated with less structural integrity ("less wiring, more firing") (Daselaar et al., 2015). A recent experiment performed by Lucas et al. (2019) found increased PFC activation from single to dual-task walking is associated with white matter structural integrity (i.e. less integrity was associated with more activity).

5.2. In the future

Moving forward, how should we test people for neural function during mobility tasks? Below we list some considerations for future experimental designs that also address the limitations discussed above:

1) Parametric variation of walking task difficulty is important for fully characterizing the relationship of behavioral performance to brain indices. For example, an older adult may show compensatory brain activity (relative to a younger adult) in standard walking, but introducing an obstacle may result in increased brain activity and substantial reduction in performance due to the inability to perform the task. According to the framework discussed above, if we were only interested in the brain-behavior relationship during the obstacle condition, we would classify this as dysfunctional neural activation. However, by increasing the obstacles incrementally, accompanying changes in brain activity can be

assessed, coupled with changes in walking performance, so that potential compensatory brain activity and its limitations can be identified. This methodology has been applied successfully in older adults in many cognitive experiments (Cappell et al., 2010; Carp et al., 2010; Reuter-Lorenz & Cappell, 2008), and has recently been investigated in walking (Clark et al., 2019).

2) Terrain modification paradigms are promising for studying how the neural control of mobility changes with age. Terrain modifications are more likely to identify the neural controls of mobility as opposed to those involved in secondary task performance. Terrain modifications could include performing a mobility task across multiple difficulty levels to probe the gradation and limits of potential compensatory brain activity. The complexity can be adjusted using uneven terrain, obstacles, or even balance perturbations (e.g., simulated falls). These terrain modifications can also be implemented in motor imagery paradigms, similar to those discussed in the section Terrain Modification: Imagined Modification.
3) We emphasize the importance of quantifying brain structure along with functional activity. An increasingly common strategy is to combine structural and functional assessment, using structural MRI with fNIRS in the same participants to determine the relationship between frontal gray matter volume and fNIRS-derived brain activation (Wagshul et al., 2019), allowing for normalization of brain activity to gray matter volume. This allows determination of whether brain activity during walking is associated with structural changes.
4) In order to develop a comprehensive understanding of the brain-behavior relationships, many factors must also be taken into consideration. Mobility requires the integration of multiple sensory systems including vision, vestibular, and proprioceptive systems (Peterka, 2002). Therefore, measurements of sensory function could inform individual differences in specific compensatory brain activity. Standard clinical tests such as Romberg eyes open and eyes closed is an efficient way to test vestibular and visual reliance for standing posture (Lanska & Goetz, 2000). Further, tactile perception can be tested with tactile discrimination tests on the feet (e.g., Semmes-Weinstein monofilaments), which is one of many important components of somatosensory function for balance. Pain is also a sensory system that can contribute to mobility and brain function (Brumagne et al., 2019), and can be efficiently and reliably measured with a general survey of pain experienced when performing the task of interest (Cruz-Almeida et al., 2017). All of these factors contribute to the individual variability in mobility function and are likely to influence compensatory and dysfunctional brain processes as well.
5) With increased understanding of how different brain areas contribute to mobility with age, we can potentially implement targeted neural interventions aimed at maintenance of mobility. For example, noninvasive brain stimulation coupled with mobility training can enhance performance. While we know some older adults may present more with neural compensation and others with neural dysfunction, a better understanding of these processes may allow for targeting different brain regions across individuals as a result.

6. Conclusion

The past two decades have brought numerous advances in the science of aging mobility. New technology has enabled the acquisition of novel types of data that can inform the neural underpinnings of mobility changes throughout the life span. Building on theoretical progress in neurocognitive aging, we applied two accounts of brain aging—neural compensation and neural dysfunction—to classify the results of published studies that combined brain activity and mobility measurements in older adults, dating back two decades. We separated the identified articles into three categories based on methodology: Single Task Assessment, Terrain Modifications, and Divided Attention Modifications. The Single Task Assessment category had the greatest proportion of results that supported compensation, followed by Terrain Modification, and finally Divided Attention. We recommend that future mobile imaging studies include multiple levels of walking complexity, structural brain images, and detailed participant history in order to understand whether the neural mechanisms associated with performance are compensatory or dysfunctional. This knowledge will lead to the ability to appropriately promote beneficial brain activity for the behavior of interest.

Consent for publication

All authors provided approval for publication.

Disclosure statement

The authors declare that they have no competing interests.

Acknowledgement

Supported by NIH (U01AG061389)

References

Allali, G., van der Meulen, M., Beauchet, O., Rieger, S.W., Vuilleumier, P., Assal, F., 2014. The neural basis of age-related changes in motor imagery of gait: an fMRI study. J Gerontol Series A, Biol Sci Med Sci. 69 (11), 1389–1398. doi:10.1093/gerona/glt207.

Bäckman, L., Dixon, R., 1992. Psychological compensation: a theoretical framework. Psychol Bull. 112, 259–283. doi:10.1037/0033-2909.112.2.259.

Baltes, P.B., Lindenberger, U., 1997. Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? Psychol Aging 12 (1), 12–21. doi:10.1037/0882-7974.12.1.12.

Bernard, J.A., Seidler, R.D., 2012. Evidence for motor cortex dedifferentiation in older adults. Neurobiol Aging 33 (9), 1890–1899. doi:10.1016/j.neurobiolaging.2011.06.021.

Beurskens, R., Helmich, I., Rein, R., Bock, O., 2014. Age-related changes in prefrontal activity during walking in dual-task situations: a fNIRS study. Int J Psychophysiol. 92 (3), 122–128. doi:10.1016/j.ijpsycho.2014.03.005.

Brown, L.A., Sleik, R.J., Polych, M.A., Gage, W.H., 2002. Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? J Gerontol Ser A Biol Sci Med Sci. 57 (12), 785–792. doi:10.1093/gerona/57.12.M785.

Brumagne, S., Diers, M., Danneels, L., Moseley, G.L., Hodges, P.W., 2019. Neuroplasticity of sensorimotor control in low back pain. J Orthop Sports Phys Ther 49 (6), 402–414. doi:10.2519/jospt.2019.8489.

Cabeza, R., Albert, M., Belleville, S., Craik, F.I.M., Duarte, A., Grady, C.L., Lindenberger, U., Nyberg, L., Park, D.C., Reuter-Lorenz, P.A., Rugg, M.D., Steffener, J., Rajah, M.N, 2018. Maintenance, reserve and compensation: the cognitive neuroscience of healthy ageing. Nat Rev Neurosci 19 (11), 701–710. doi:10.1038/s41583-018-0068-2.

Cabeza, R., Mangels, J., Nyberg, L., Habib, R., Houle, S., McIntosh, A.R., Tulving, E., 1997. Brain regions differentially involved in remembering what and when: a PET study. Neuron 19 (4), 863–870. doi:10.1016/S0896-6273(00)80967-8.

Cabeza, R., Prince, S.E., Daselaar, S.M., Greenberg, D.L., Budde, M., Dolcos, F., LaBar, K.S., Rubin, D.C., 2004. Brain activity during episodic retrieval of autobiographical and laboratory events: an fMRI study using a novel photo paradigm. J Cogn Neurosci. 16 (9), 1583–1594. doi:10.1162/0898929042568578.

Calautti, C., Serrati, C., Baron, J.C., 2001. Effects of age on brain activation during auditory-cued thumb-to-index opposition: a positron emission tomography study. Stroke 32 (1), 139–146. doi:10.1161/01.STR.32.1.139.

Cappell, K., Gmeindl, L., Reuter-Lorenz, P., 2010. Age Differences in Prefontal Recruitment During Verbal Working Memory Maintenance Depend on Memory Load. Cortex 46 (4), 462–473. doi:10.1038/mp.2011.182.doi.

Carp, J., Gmeindl, L., Reuter-Lorenz, P.A., 2010. Age differences in the neural representation of working memory revealed by multi-voxel pattern analysis. Front Human Neurosci 4, 217. doi:10.3389/fnhum.2010.00217.

Carp, J., Park, J., Hebrank, A., Park, D.C., Polk, T.A., 2011. Age-related neural dedifferentiation in the motor system. PloS One 6 (12), e29411. doi:10.1371/journal.pone.0029411.

Cassady, K., Gagnon, H., Lalwani, P., Simmonite, M., Foerster, B., Park, D., Peltier, S.J., Petrou, M., Taylor, S.F., Weissman, D.H., Seidler, R.D., Polk, T.A., 2019. Sensorimotor network segregation declines with age and is linked to GABA and to sensorimotor performance. NeuroImage 186, 234–244. doi:10.1016/j.neuroimage.2018.11.008.

Chen, M., Pillemer, S., England, S., Izzetoglu, M., Mahoney, J.R., Holtzer, R., 2017. Neural correlates of obstacle negotiation in older adults: an fNIRS study. Gait Posture 58, 130–135. doi:10.1016/j.gaitpost.2017.07.043.

Clark, D.J., Christou, E.A., Ring, S.A., Williamson, J.B., Doty, L., 2014. Enhanced somatosensory feedback reduces prefrontal cortical activity during walking in older adults. J Gerontol A Biol Sci Med Sci. 69 (11), 1422–1428. doi:10.1093/gerona/glu125.

Clark, D.J., Manini, T.M., Ferris, D.P., Hass, C.J., Brumback, B.A., Cruz-Almeida, Y., Pahor, M., Reuter-Lorenz, P.A., Seidler, R.D., 2019. Multimodal imaging of brain activity to investigate walking and mobility decline in older adults (mind in motion study): hypothesis, theory, and methods. Front Aging Neurosci. 11. doi:10.3389/fnagi.2019.00358.

Clark, D.J., Rose, D.K., Ring, S.A., Porges, E.C., 2014. Utilization of central nervous system resources for preparation and performance of complex walking tasks in older adults. Front Aging Neurosci 6. doi:10.3389/fnagi.2014.00217.

Cruz-Almeida, Y., Rosso, A., Marcum, Z., Harris, T., Newman, A.B., Nevitt, M., Satterfield, S., Yaffe, K., Rosano, C.for the Health ABC Study, 2017. Associations of musculoskeletal pain with mobility in older adults: potential cerebral mechanisms. J Gerontol A. 72 (9), 1270–1276. doi:10.1093/gerona/glx084.

Daselaar, S.M., Iyengar, V., Davis, S.W., Eklund, K., Hayes, S.M., Cabeza, R.E., 2015. Less wiring, more firing: low-performing older adults compensate for impaired white matter with greater neural activity. Cereb Cortex 25 (4), 983–990. doi:10.1093/cercor/bht289.

Dustman, R.E., Emmerson, R.Y., Shearer, D.E., 1996. Life span changes in electrophysiological measures of inhibition. Brain Cogn. 30 (1), 109–126. doi:10.1006/brcg.1996.0007.

Eysel, U.T., Shevelev, I.A., Lazareva, N.A., Sharaev, G.A., 1998. Orientation tuning and receptive field structure in cat striate neurons during local blockade of intracortical inhibition. Neurosci. 84 (1), 25–36. doi:10.1016/S0306-4522(97)00378-3.

Fernandez, N.B., Hars, M., Trombetti, A., Vuilleumier, P., 2019. Age-related changes in attention control and their relationship with gait performance in older adults with high risk of falls. NeuroImage 189, 551–559. doi:10.1016/j.neuroimage.2019.01.030.

Florence, C.S., Bergen, G., Atherly, A., Burns, E., Stevens, J., Drake, C., 2018. The medical costs of fatal falls and fall injuries among older adults. J Am Geriatr Soc 66 (4), 693–698. doi:10.1111/jgs.15304.

Fraser, S.A., Dupuy, O., Pouliot, P., Lesage, F., Bherer, L., 2016. Comparable cerebral oxygenation patterns in younger and older adults during dual-task walking with increasing load. Front Aging Neurosci 8. doi:10.3389/fnagi.2016.00240.

Godde, B., Voelcker-Rehage, C., 2010. More automation and less cognitive control of imagined walking movements in high- versus low-fit older adults. Front Aging Neurosci 2 (SEP), 1–13. doi:10.3389/fnagi.2010.00139.

Gonzalez-Burgos, L., Hernández-Cabrera, J.A., Westman, E., Barroso, J., Ferreira, D., 2019. Cognitive compensatory mechanisms in normal aging: a study on verbal fluency and the contribution of other cognitive functions. Aging 11 (12), 4090–4106. doi:10.18632/aging.102040.

Grady, C., 2012. The cognitive neuroscience of ageing. Nat Rev Neurosci. 13 (7), 491–505. doi:10.1038/nrn3256.

Grady, C.L., Maisog, J.M., Horwitz, B., Ungerleider, L.G., Mentis, M.J., Salerno, J.A., Pietrini, P., Wagner, E., Haxby, J.V., 1994. Age-related changes in cortical blood flow activation during visual processing of faces and location. J Neurosci 14 (3 II), 1450–1462. doi:10.1523/jneurosci.14-03-01450.1994.

Grady, C.L., Randy McIntosh, A., Horwitz, B., Rapoport, S.I, 2000. Age-related changes in the neural correlates of degraded and nondegraded face processing. Cogn Neuropsychol 17 (1–3), 165–186. doi:10.1080/026432900380553.

Hamacher, D., Herold, F., Wiegel, P., Hamacher, D., Schega, L., 2015. Brain activity during walking: a systematic review. Neurosci Biobehav Rev 57, 310–327. doi:10.1016/j.neubiorev.2015.08.002.

Hausdorff, J.M., Rios, D.A., Edelberg, H.K., 2001. Gait variability and fall risk in community-living older adults: A 1-Year prospective study 82 (8), 1050–1056 doi:10.1053/apmr.2001.24893.

Hausman, H.K., Jackson, T.B., Goen, J.R.M., Bernard, J.A, 2019. From synchrony to asynchrony: cerebellar–basal ganglia functional circuits in young and older adults. Cereb Cortex 00, 1–12. doi:10.1093/cercor/bhz121.

Hawkins, K.A., Fox, E.J., Daly, J.J., Rose, D.K., Christou, E.A., McGuirk, T.E., Otzel, D.M., Butera, K.A., Chatterjee, S.A., Clark, D.J., 2018. Prefrontal over-activation during walking in people with mobility deficits: interpretation and functional implications. Hum Mov Sci. 59, 46–55. doi:10.1016/j.humov.2018.03.010.

Hedman, A.M., van Haren, N.E.M., Schnack, H.G., Kahn, R.S., Hulshoff Pol, H.E., 2012. Human brain changes across the life span: a review of 56 longitudinal magnetic resonance imaging studies. Hum Brain Mapp 33 (8), 1987–2002. doi:10.1002/hbm.21334.

Heinzel, S., Lorenz, R.C., Brockhaus, W.-R., Wustenberg, T., Kathmann, N., Heinz, A., Rapp, M.A., 2014. Working memory load-dependent brain response predicts behavioral training gains in older adults. J Neurosci 34 (4), 1224–1233. doi:10.1523/jneurosci.2463-13.2014.

Heuninckx, S., Wenderoth, N., Swinnen, S.P., 2008. Systems neuroplasticity in the aging brain: recruiting additional neural resources for successful motor performance in elderly persons. J Neurosci. 28 (1), 91–99. doi:10.1523/JNEUROSCI.3300-07.2008.

Holtzer, R., Epstein, N., Mahoney, J.R., Izzetoglu, M., Blumen, H.M., 2014. Neuroimaging of mobility in aging: a targeted review. J Gerontol Ser A Biol Sci Med Sci. 69 (11), 1375–1388. doi:10.1093/gerona/glu052.

Holtzer, R., Kraut, R., Izzetoglu, M., Ye, K., 2019. The effect of fear of falling on prefrontal cortex activation and efficiency during walking in older adults. GeroSci. 41 (1), 89–100. doi:10.1007/s11357-019-00056-4.

Holtzer, R., Mahoney, J.R., Izzetoglu, M., Izzetoglu, K., Onaral, B., Verghese, J., 2011. FNIRS study of walking and walking while talking in young and old individuals. J Gerontol Ser A Biol Sci Med Sci. 66 A (8), 879–887. doi:10.1093/gerona/glr068.

Holtzer, R., Mahoney, J.R., Izzetoglu, M., Wang, C., England, S., Verghese, J., 2015. Online fronto-cortical control of simple and attention-demanding locomotion in humans. NeuroImage 112, 152–159. doi:10.1016/j.neuroimage.2015.03.002.

Holtzer, R., Verghese, J., Allali, G., Izzetoglu, M., Wang, C., Mahoney, J.R., 2016. Neurological gait abnormalities moderate the functional brain signature of the posture first hypothesis. Brain Topogr. 29 (2), 334–343. doi:10.1007/s10548-015-0465-z.

Jahn, K., Deutschländer, A., Stephan, T., Kalla, R., Wiesmann, M., Strupp, M., Brandt, T., 2008. Imaging human supraspinal locomotor centers in brainstem and cerebellum. NeuroImage 39 (2), 786–792. doi:10.1016/j.neuroimage.2007.09.047.

Jahn, K., Deutschländer, A., Stephan, T., Strupp, M., Wiesmann, M., Brandt, T., 2004. Brain activation patterns during imagined stance and locomotion in functional magnetic resonance imaging. NeuroImage 22 (4), 1722–1731. doi:10.1016/j.neuroimage.2004.05.017.

Jor'dan, A.J., Poole, V.N., Iloputaife, I., Milberg, W., Manor, B., Esterman, M., Lipsitz, L.A., 2017. Executive network activation is linked to walking speed in older adults: functional MRI and TCD ultrasound evidence from the MOBILIZE Boston Study. J Gerontol Ser A Biol Sci Med Sci. 72 (12), 1669–1675. doi:10.1093/gerona/glx063.

Kawagoe, T., Suzuki, M., Nishiguchi, S., Abe, N., Otsuka, Y., Nakai, R., Yamada, M., Yoshikawa, S., Sekiyama, K., 2015. Brain activation during visual working memory correlates with behavioral mobility performance in older adults. Front Aging Neurosci. 7, 186. doi:10.3389/fnagi.2015.00186.

King, B.R., Van Ruitenbeek, P., Leunissen, I., Cuypers, K., Heise, K.F., Santos Monteiro, T., Hermans, L., Levin, O., Albouy, G., Mantini, D., Swinnen, S.P., 2018. Age-related declines in motor performance are associated with decreased segregation of large-scale resting state brain networks. Cereb Cortex 28 (12), 4390–4402. doi:10.1093/cercor/bhx297.

Koen, J.D., Rugg, M.D., 2019. Neural dedifferentiation in the aging brain. Trends Cogn. Sci. 23 (7), 547–559. doi:10.1016/j.tics.2019.04.012.

la Fougère, C., Zwergal, A., Rominger, A., Förster, S., Fesl, G., Dieterich, M., Brandt, T., Strupp, M., Bartenstein, P., Jahn, K., 2010. Real versus imagined locomotion: A [18F]-FDG PET-fMRI comparison. NeuroImage 50 (4), 1589–1598. doi:10.1016/j.neuroimage.2009.12.060.

Lanska, D.J., Goetz, C.G., 2000. Romberg's sign: development, adoption, and adaptation in the 19th century. Neurology 55 (8), 1201–1206. doi:10.1212/WNL.55.8.1201.

Li, K., Bherer, L., Mirelman, A., Maidan, I., Hausdorff, J.M., 2018. Cognitive involvement in balance, gait and dual-tasking in aging: a focused review from a neuroscience of aging perspective. Front Neurol. 9, 913. doi:10.3389/fneur.2018.00913.

Li, K.Z.H., Lindenberger, U, 2002. Relations between aging sensory/sensorimotor and cognitive functions. Neurosci Biobehav Rev 26 (7), 777–783. doi:10.1016/S0149-7634(02)00073-8.

Li, S.C., Lindenberger, U., Sikström, S., 2001. Aging cognition: from neuromodulation to representation. Trends Cogn Sci 5 (11), 479–486. doi:10.1016/S1364-6613(00)01769-1.

Li, S.-C., Lindenberger, U., 1999. Cross-level unification:Computational exploration of the link between deterioration of neurotransmitter and dedifferenciation of cognition in old age Cogn Neuroscience Memory, 103–146.

Lindenberger, U., Baltes, P.B., 1994. Sensory functioning and intelligence in old age: a strong connection. Psychol Aging 9 (3), 339–355. doi:10.1037/0882-7974.9.3.339.

Lövdén, M., Schaefer, S., Pohlmeyer, A.E., Lindenberger, U., 2008. Walking variability and working-memory load in aging: a dual-process account relating cognitive control to motor control performance. J Gerontol Ser B Psychol Sci Soc Sci. 63 (3). doi:10.1093/geronb/63.3.P121.

Madden, D.J., Turkington, T.G., Provenzale, J.M., Denny, L.L., Hawk, T.C., Gottlob, L.R., Coleman, R.E., 1999. Adult age differences in the functional neuroanatomy of verbal recognition memory. Hum Brain Mapp 7 (2), 115–135. doi:10.1002/(SICI)1097-0193(1999)7:2⟨115::AID-HBM5⟩3.0.CO;2-N.

Mattay, V.S., Fera, F., Tessitore, A., Hariri, A.R., Das, S., Callicott, J.H., Weinberger, D.R., 2002. Neurophysiological correlates of age-related changes in human motor function. Neurology 58 (4), 630–635. doi:10.1212/WNL.58.4.630.

Mattay, Venkata.S., Fera, F., Tessitore, A., Hariri, A.R., Berman, K.F., Das, S., Meyer-Lindenberg, A., Goldberg, T.E., Callicott, J.H., Weinberger, D.R., 2006. Neurophysiological correlates of age-related changes in working memory capacity. Neurosci Lett. 392 (1–2), 32–37. doi:10.1016/j.neulet.2005.09.025.

Melie-Garcia, L., Slater, D., Ruef, A., Sanabria-Diaz, G., Preisig, M., Kherif, F., Draganski, B., Lutti, A., 2018. Networks of myelin covariance. Hum Brain Mapp 39 (4), 1532–1554. doi:10.1002/hbm.23929.

Meunier, D., Stamatakis, E.A., Tyler, L.K., 2014. Age-related functional reorganization, structural changes, and preserved cognition. Neurobiol Aging 35 (1), 42–54. doi:10.1016/j.neurobiolaging.2013.07.003.

Mirelman, A., Maidan, I., Bernad-Elazari, H., Shustack, S., Giladi, N., Hausdorff, J.M, 2017. Effects of aging on prefrontal brain activation during challenging walking conditions. Brain Cogn 115, 41–46. doi:10.1016/j.bandc.2017.04.002.

Mitchell, T., Starrs, F., Soucy, J.-P., Thiel, A., Paquette, C., 2019. Impaired sensorimotor processing during complex gait precedes behavioral changes in middle-aged adults. J Gerontol Ser A, Biol Sci Med Sci. 74 (12), 1861–1869. doi:10.1093/gerona/gly210.

Osofundiya, O., Benden, M.E., Dowdy, D., Mehta, R.K., 2016. Obesity-specific neural cost of maintaining gait performance under complex conditions in community-dwelling older adults. Clin Biomech (Bristol, Avon) 35, 42–48. doi:10.1016/j.clinbiomech.2016.03.011.

Peterka, R.J., 2002. Sensorimotor integration in human postural control. J Neurophysiol. 88 (3), 1097–1118. doi:10.1152/jn.2002.88.3.1097.

Reuter-Lorenz, P.A., Cappell, K.A., 2008. Neurocognitive aging and the compensation hypothesis. Curr Direct Psychol Sci 17 (3), 177–182. doi:10.1111/j.1467-8721.2008.00570.x.

Reuter-Lorenz, P.A., Jonides, J., Smith, E.E., Hartley, A., Miller, A., Marshuetz, C., Koeppe, R.A., 2000. Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. J Cogn Neurosci. 12 (1), 174–187. doi:10.1162/089892900561814.

Reuter-Lorenz, P.A., Stanczak, L., Miller, A.C., 1999. Neural recruitment and cognitive aging: two hemispheres are better than one, especially as you age.. Psychol Sci. 10 (6), 494–500. doi:10.1111/1467-9280.00195.

Sakurai, R., Fujiwara, Y., Yasunaga, M., Takeuchi, R., Murayama, Y., Ohba, H., Sakuma, N., Suzuki, H., Oda, K., Sakata, M., Toyohara, J., Ishiwata, K., Shinkai, S., Ishii, K., 2014. Regional cerebral glucose metabolism and gait speed in healthy community-dwelling older women. J Gerontol Ser A, Biol Sci Med Sci. 69 (12), 1519–1527. doi:10.1093/gerona/glu093.

Sakurai, R., Ishii, K., Yasunaga, M., Takeuchi, R., Murayama, Y., Sakuma, N., Sakata, M., Oda, K., Ishibashi, K., Ishiwata, K., Fujiwara, Y., Montero-Odasso, M., 2017. The neural substrate of gait and executive function relationship in elderly women: a PET study. Geriatr Gerontol Int 17 (11), 1873–1880. doi:10.1111/ggi.12982.

Sato, H., Katsuyama, N., Tamura, H., Hata, Y., Tsumoto, T., 1996. Mechanisms underlying orientation selectivity of neurons in the primary visual cortex of the macaque. J Physiol 494 (3), 757–771. doi:10.1113/jphysiol.1996.sp021530.

Schmolesky, M.T., Wang, Y., Pu, M., Leventhal, A.G., 2000. Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. Nat Neurosci. 3 (4), 384–390. doi:10.1038/73957.

Schneider-Garces, N.J., Gordon, B.A., Brumback-Peltz, C.R., Shin, E., Lee, Y., Sutton, B.P., Maclin, E.L., Gratton, G., Fabiani, M., 2010. Span, CRUNCH, and beyond: working memory capacity and the aging brain. J Cogn Neurosci. 22 (4), 655–669. doi:10.1162/jocn.2009.21230.

Schulz, B.W., 2012. Healthy younger and older adults control foot placement to avoid small obstacles during gait primarily by modulating step width. J NeuroEng Rehabil. 9 (1), 69. doi:10.1186/1743-0003-9-69.

Seidler, R.D., Bernard, J.A., Burutolu, T.B., Fling, B.W., Gordon, M.T., Gwin, J.T., Kwak, Y., Lipps, D.B., 2010. Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. Neurosci Biobehav Rev 34 (5), 721–733. doi:10.1016/j.neubiorev.2009.10.005.

Shimada, H., Ishii, K., Ishiwata, K., Oda, K., Suzukawa, M., Makizako, H., Doi, T., Suzuki, T., 2013. Gait adaptability and brain activity during unaccustomed treadmill walking in healthy elderly females. Gait Posture 38 (2), 203–208. doi:10.1016/j.gaitpost.2012.11.008.

Shumway-Cook, A., Patla, A.E., Stewart, A., Ferrucci, L., Ciol, M.A., Guralnik, J.M., 2002. Environmental demands associated with community mobility in older adults with and without mobility disabilities. Phys Ther 82 (7), 670–681. doi:10.1093/ptj/82.7.670.

Spedden, M.E., Choi, J.T., Nielsen, J.B., Geertsen, S.S., 2019. Corticospinal control of normal and visually guided gait in healthy older and younger adults. Neurobiol Aging 78, 29–41. doi:10.1016/j.neurobiolaging.2019.02.005.

Stuart, S., Alcock, L., Rochester, L., Vitorio, R., Pantall, A., 2019. Monitoring multiple cortical regions during walking in young and older adults: Dual-task response and comparison challenges. Int J Psychophysiol 135, 63–72. doi:10.1016/j.ijpsycho.2018.11.006.

Vitorio, R., Stuart, S., Gobbi, L.T.B., Rochester, L., Alcock, L., Pantall, A, 2018. Reduced gait variability and enhanced brain activity in older adults with auditory cues: a functional near-infrared spectroscopy study. Neurorehabil Neural Repair 32 (11), 976–987. doi:10.1177/1545968318805159.

Wagshul, M.E., Lucas, M., Ye, K., Izzetoglu, M., Holtzer, R., 2019. Multi-modal neuroimaging of dual-task walking: Structural MRI and fNIRS analysis reveals prefrontal grey matter volume moderation of brain activation in older adults. NeuroImage 189, 745–754. doi:10.1016/j.neuroimage.2019.01.045.

Wai, Y.-Y., Wang, J.-J., Weng, Y.-H., Lin, W.-Y., Ma, H.-K., Ng, S.-H., Wan, Y.-L., Wang, C.-H., 2012. Cortical involvement in a gait-related imagery task: comparison between Parkinson's disease and normal aging. Parkinsonism Relat Disord. 18 (5), 537–542.

Ward, N.S., Frackowiak, R.S.J, 2013. Age-related changes in the neural correlates of motor performance. Brain 126 (0 4), 873–888. doi:10.1093/brain/awg071.

Wittenberg, E., Thompson, J., Nam, C.S., Franz, J.R., 2017. Neuroimaging of human balance control: a systematic review. Front Hum Neurosci. 11. doi:10.3389/fnhum.2017.00170.